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POWER DISTRIBUTION ALTERNATIVES IN CANADIAN RAILWAY ELECTRIFICATION

G.W. English
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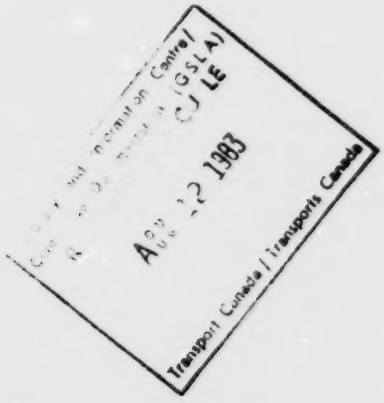

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17. Abstract

The study undertakes an evaluation of the alternative voltages and frequencies which may be used to distribute electrical power, if the Canadian railways electrify. The Canadian railway system is divided into three candidate regions (mountain, prairie and corridor), average values for the relevant parameters within each region are estimated, and a separate evaluation of the distribution alternatives for each is undertaken. Particular attention is paid to the means of attaining a satisfactory load imbalance at the electrical utility connection. The costs relevant to the distribution decision are aggregated on the basis of net present value per route-kilometer, and a sensitivity analysis of key parameters is performed. Recommendations are made on the basis of this financial analysis.

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17. Resume

Ce rapport décrit les travaux d'évaluation des diverses solutions envisagées en matière d'alimentation, à savoir la tension et la fréquence du courant électrique devant alimenter le réseau Canadien de chemins de fer dans l'éventualité de son électrification. Le réseau ferroviaire étant subdivisé en trois régions distinctes: montagne, prairie, corridor ferroviaire, le rapport décrit à l'égard de chacune des trois régions visées la méthode d'estimation des valeurs moyennes des divers paramètres retenus et d'évaluation de chacune des solutions envisagées, une attention particulière ayant été donnée à la meilleure manière de réduire au maximum le déséquilibre de charge au point de branchement sur le réseau de l'entreprise d'utilité publique. Les éléments importants du coût de chacune de ces solutions sont ensuite dégagés et leur valeur actuelle nette par kilomètre déterminée, le tout complété d'une analyse de sensibilité à l'égard des facteurs clés. Néanmoins, des recommandations sont faites, fondées sur cette analyse financière.

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1. INTRODUCTION

Many railway electrification studies have been done to date assuming a working voltage and frequency from conventional practice elsewhere or from reports from other studies. The most common assumptions in North America are to energize the catenary at a nominal voltage of 25 kV, commercial frequency, or, in some cases, 50 kV, also at the commercial frequency of 60 Hz.

In the renewed interest by Canadian railways in the 1970's, much attention was paid to developing cost data based on the 50 kV alternative. At that time, only a crude relationship affecting the choice of voltage was considered, namely, that at 50 kV there should be a longer spacing between substations and therefore the cost of power supply should be reduced. No thorough engineering analysis of the parameters affecting physical design and cost as a result of the choice of voltage and frequency had been made. Although the general relationships were well known between voltage, current/energy demand, conductor size, and insulator length or electrical clearance, the choice of voltage was still a cut-and-try affair whereby a design was tried at both popular voltages to see which resulted in lower cost.

This study sets out to provide a rational analysis for the selection of voltage and frequency. Some consideration is given to options other than the popular 25 and 50 kV options, specifically a direct-current option and a lower-frequency alternating-current option -- 12.5 kV direct current and 25 kV at a lower frequency of 25 Hz. This analysis considers these two additional options in lesser detail but, in view of the preliminary results, it concentrates on an in-depth analysis of the trade-offs relating to the choice between 25 kV, 60 Hz, and 50 kV, 60 Hz.

For readers unfamiliar with the terminology which is used in the report, a glossary is located in Appendix G.

2. THE STUDY APPROACH

With any system study one experiences diminishing returns and extra costs to obtain finer detail in the representation of the system. In this study it was desirable to evaluate the relative attractiveness of the various distribution alternatives for the complete railway system. However, the timing and scope of the study did not permit the development of detailed data on unit costs and physical quantities for the complete system. As a result, representative characteristics of the diverse Canadian railway network were estimated, and readily available unit cost estimates were applied in the evaluation. The Canadian railway system was divided into three candidate regions (mountain, prairie and corridor). Average values for the relevant parameters within each region were estimated, and a separate evaluation of the electrical distribution alternatives for each was undertaken. The most important parameters in the distribution decision are: (1) the nature of the electrical load, (2) the single-phase load limit imposed by the utility and (3) the clearance obstructions which exist. The three chosen regions exhibit distinctly different characteristics.

The nature of the electrical load depends on the traffic characteristics. The substation serving a section of track will have a power demand which varies with time as different combinations of trains traverse the track segment. The number of trains per day which traverse the rail line, the power demand of the specific trains, and the train speed (which determines the duration of the load) are the important parameters influencing the substation.

Canadian railways operate a variety of train configurations. The configurations are influenced by many factors, including cargo characteristics, cargo flow, travel distances, track gradient and curvature, schedules, and track capacity. Typically, freight trains operate with multiple-unit diesel power, but at relatively low speeds. Train and track characteristics often limit train speeds to 80 km/h or less. Express trains, usually moving higher-value cargo, operate at speeds of 100 km/h when conditions permit. Although the total express train weight is less than that of a freight train, the higher speed and tighter schedule impose power requirements which force multiple unit

operation. Passenger trains represent a small portion of the total rail traffic in all areas except the Toronto-Montreal corridor.

The use of high power levels for individual trains would impose a severe load problem on an electrified line. Electric current demands are more severe, requiring heavier wire and larger catenary feed equipment, and imposing higher peak power demands, with their consequent financial penalties. Shorter, lighter trains would reduce the demands on an electrified system. However, the lighter trains mean more trains, with more crew. Track capacity and crew costs are adversely affected.

To be acceptable to the Canadian railways, rail electrification should not force modification of train and traffic patterns to any substantial extent. Thus, while short-train operations were evaluated as one parameter variation in a sensitivity analysis, the base case evaluation assumed the existing operating strategy.

Six train types, with the characteristics shown in Table 2.1, were considered in the analysis. As both railways are undertaking track upgrading in the west, with double-tracking and gradient reduction programs, the analysis was performed on the basis of each region having full double track and not more than a one per cent ruling gradient. This means that the same power-to-weight ratio may be used in each region. Different numbers of each train type were used in each region.

TABLE 2.1

TRAIN CHARACTERISTICS

Type	Average Gross Tons per Car	Average Cars per Train	Average Horsepower per GTT	Average MW per Train
Bulk loaded	125	100	1.0	9.5
Bulk empty	31	100	1.4	3.5
Mixed freight	70	100	1.4	7.6
Express	50	70	2.2	6.2
Normal passenger	n/a	n/a	n/a	4.0
High-speed passenger	n/a	n/a	n/a	5.6

The traffic levels, the splits by train type, and the average speeds are shown in Table 2.2. The mountain region has the highest tonnage density (i.e. tonnage moved per km of track), the lowest average speed and the highest component of bulk traffic. The corridor region has the lowest tonnage with the highest average speed and the highest component of passenger and express freight. Also shown in the table are the estimated utility imbalance limits (i.e. the maximum load which can be taken with a single-phase tap) and electromagnetic compatibility (EMC) measures taken.

TABLE 2.2

REGION CHARACTERISTICS

Region	Freight Traffic Level (MGT/annum)		Freight Traffic Split (bulk/mixed) (/express)	Passenger Traffic (trains/day)				Weighted Average Speed (km/h)	Utility Imbalance Limit (MVA)	EMC Measures
				Year 1		Year 30				
	Year 1	Year 30		(1)	(2)	(1)	(2)			
Mountain	60	100	.7/.2/.1	2	0	2	0	48	10-20	return wire
Prairie	45	74	.6/.3/.1	2	0	2	0	75	10-20	return wire
Corridor	30	50	.1/.5/.4	9	7	26	12	100	30-60	booster transformer

(1) normal passenger train
(2) high-speed passenger train

The actual imbalance limits are not known because a standard has not been set in Canada for a railway load. The existing NEMA-recommended standard is for a continuous load imbalance of one per cent of the utility three-phase fault input at the utility connection point. European standards for railway loads permit three per cent imbalance and the Canadian utilities may adopt this level. Some three-phase fault levels have been obtained from Ontario Hydro for the corridor region and from Manitoba Hydro for the southern part of that province. The range was 1575 to 4600 MVA for the corridor region and 230 to 1390 MVA for Manitoba. The other Prairie provinces and B.C. were estimated

to have similar values to those of Manitoba. The load imbalances shown in Table 2.2 were estimated to be the probable range for most locations in each region, and they permit a large enough variance to demonstrate the implications of load imbalance for the distribution decision. It is possible, however, that some sites may be higher or lower than the range shown in the table.

The EMC measures taken affect both the unit cost of the catenary and the catenary impedance, which in turn affects the substation spacing. The utility imbalance and EMC measures will be discussed in more detail in the next section.

What voltage and frequency should be used on railway property to transmit power from the electrical utility supply point to the points of use? Four alternatives, covering a reasonable selection of these variables, were evaluated. The alternatives considered are: 50 kV at 60 Hz, 25 kV at 60 Hz, 25 kV at 25 Hz, and 12.5 kV dc. While the dc option is not yet technically feasible at 12.5 kV (3 kV systems exist and 6 kV is experimental) due to locomotive and switchgear constraints, it was evaluated to determine its attractiveness in the event that appropriate technical developments should occur. For the dc system, the locomotive must reduce the supply line voltage to, at most, 1.5 kV dc for the traction motors. Chopper circuits cannot isolate the motors from momentary application of the line voltage and there are volume constraints in using inverter circuitry to produce an ac voltage which would then require all of the standard ac locomotive equipment. However, development work is in progress in several places around the world, in an attempt to raise the present 3 kV dc voltage limitation, and breakthroughs may come. The 12.5 kV option was selected because it might be possible to utilize chopper circuitry in combination with series-connected traction motors on six-axle locomotives.

3. THE RELEVANT PARAMETERS

The costs relevant to the distribution decision are those associated with the following items:

- substation and utility feed
- catenary
- civil reconstruction for electrical clearance
- modifications to achieve electromagnetic compatibility
- electric utility charges
- fixed facilities maintenance.

In general, a lower voltage has a reduced clearance requirement and therefore lower civil reconstruction costs. However, electric locomotives can only operate over a limited voltage range -- the AREA recommendation is 0.8 to 1.05 of the nominal voltage rating. For a specific power demand, the lower distribution voltage has a higher current which in turn means a higher voltage drop across the catenary impedance. As a result, the feeding distance of the lower voltage is reduced and more substation connections are required. A lower frequency permits increased substation spacing, because much of the catenary voltage drop is due to the catenary reactance, which is directly proportional to frequency. Also, undesired induction into wayside conductors is reduced in proportion to the frequency decrease. Offsetting these advantages of lower frequency is the need for additional conversion equipment at each substation.

This section will discuss each of the relevant cost parameters, outlining the estimates and assumptions made in determining the relationship which each has to the decision variables -- voltage and frequency.

3.1 CATENARY

In the context of this report, the catenary provides an overhead electrical supply to the railway locomotive. In its simplest form, the

catenary may consist of a single 'trolley' wire, supported by wayside structures at regular intervals. The locomotive current collector, commonly known as the pantograph, provides a sliding contact with the overhead contact wire. Because a simple trolley wire assumes a natural catenary shape between its supports, the pantograph contact strip must move up and down as the locomotive progresses, to maintain contact between the supply conductors and the contact strip. The ability of present designs to meet the dynamics requirements limits application of the simple trolley wire to locomotive speeds of less than 120 km/h, provided the current loading is sufficiently light to permit use of a small contact wire.[1]

For higher-speed operation, the catenary contact wire is supported by a messenger wire, so that the contact wire elevation above the track is essentially constant. Figure 3.1 illustrates four common overhead systems. The 'simple' design meets some of the dynamic requirements for higher locomotive speeds, but the variation in the relative stiffness of the catenary between support points and centre span causes some loss of contact at higher speeds. The 'sagged simple' design modifies some of the dynamic characteristics, but still fails to meet all requirements for the passenger speeds contemplated. The addition of a stitch wire (see the 'stitched' catenary of Figure 3.1) to the sagged simple design results in a small increase in installation cost, but provides a catenary wire system meeting the dynamic requirements necessary for 200 km/h locomotive operation. The compound design shown adds additional complexity and cost which is unnecessary for the Canadian application. Thus, for corridors subject to passenger service, the 'stitched sagged simple' catenary design is recommended. The 'sagged simple' catenary design is recommended for other mainline areas.

3.1.1 Catenary Current Capacity

The catenary system must be able to supply the power required by the train operation. Table 2.1 suggests a power requirement of up to 9.5 MW per train, on average. Most freight and express trains would require two electric locomotives. However, the actual power demand by a single train will depend on train configuration, terrain characteristics, traffic characteristics, and train speed.

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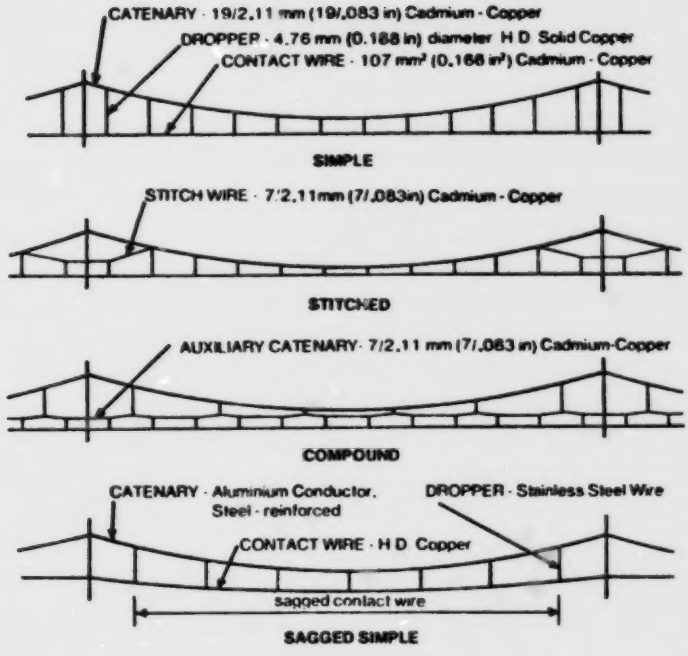
1 Carbon Brushes and Electrical Machines, Morganite Electrical Carbon Limited, p. 271.


CATENARY - 19/2.11 mm (19/.083 in) Cadmium - Copper
DROPPER - 4.76 mm (0.188 in) diameter H D Solid Copper
CONTACT WIRE - 107 mm² (0.166 in²) Cadmium - Copper
SIMPLE
STITCH WIRE - 7/2.11mm (7/.083in) Cadmium - Copper
STITCHED
AUXILIARY CATENARY - 7/2.11 mm (7/.083 in) Cadmium-Copper
COMPOUND
CATENARY - Aluminium Conductor, Steel - reinforced
DROPPER - Stainless Steel Wire
CONTACT WIRE - H D Copper
sagged contact wire
SAGGED SIMPLE

(The inclusion of wire sizes and metals is for relative comparisons and such data are not necessarily specific to any particular installations).

Source: Morganite, op. cit., p. 270

Figure 3.1 Overhead systems

In low traffic areas, the catenary may feed power to only one train at any given time. In higher traffic areas, it may be necessary to supply power to several trains simultaneously.

Figure 3.2 illustrates the maximum power demand and output of a typical electric locomotive, rated at 3600 kW output. With a rated top speed of 120 km/h, it is evident that the locomotive is geared for express freight service. A change in gear ratio, to improve locomotive operation for freight or passenger service, would reduce or expand the horizontal scale of Figure 3.2, but it would not change the vertical scales.

The train power ratings of Table 2.1 are based on diesel power ratings. Two such electric locomotives, with the overload capability,

could meet the power requirements of all trains identified in Table 2.1, if traction limits permit.

Note that the peak current demand of such a locomotive on a 25 kV catenary is close to 260 amperes under overload conditions. Thus, for freight operations, a 25 kV catenary must be able to supply up to 520 amperes to each train, if the catenary system is not to limit train performance.

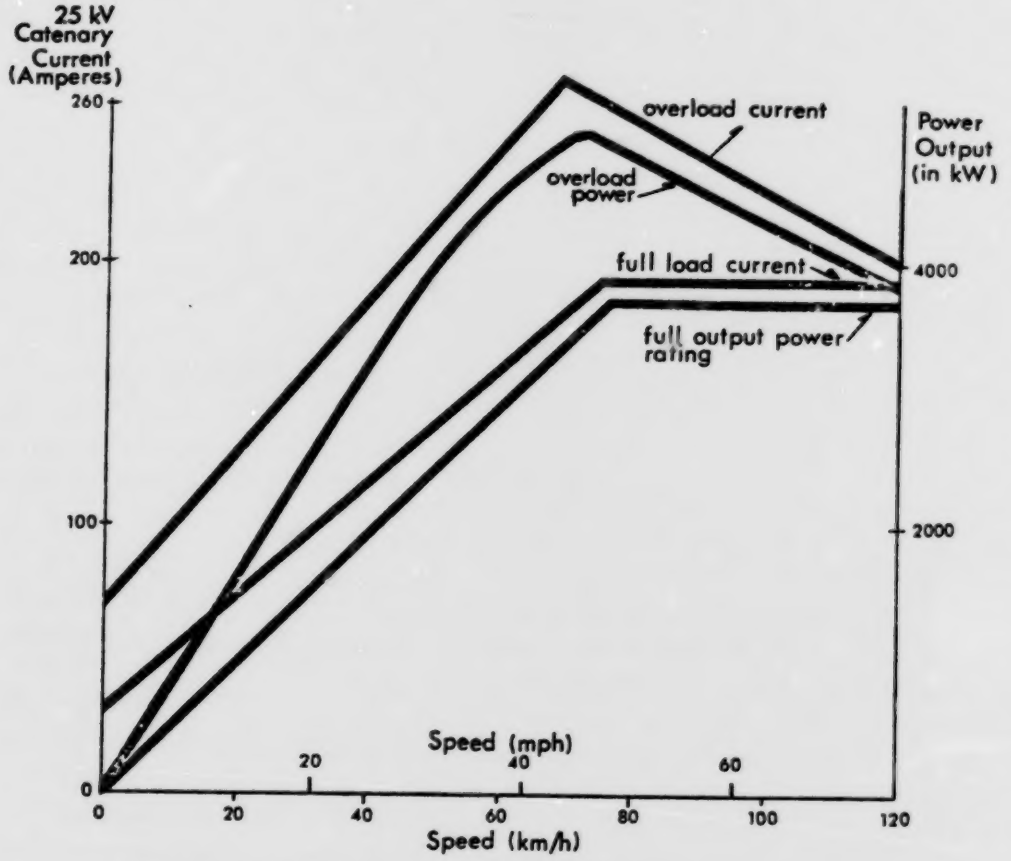


Figure 3.2 Power demand and output of a typical 3,600 kW electric locomotive

The local current capacity for a single train is determined by the contact and messenger wire assembly. However, with two catenaries on double track or with parallel feed wires, the current may be fed to a single train from each direction, thereby reducing the local required

capacity of the messenger-contact wire pair to some extent. The effectiveness of the parallel feeds is proportional to the spacing between the tie points. A shorter spacing improves the balance of the current split and also reduces the duration of the current demand on a catenary section. This latter factor is important since the current capacity is a thermal constraint and overloads of short duration are acceptable. The local current demand for one catenary at a tie point of a double track system would go from 50 per cent to 100 per cent of the total train current demand as the train approaches from the adjacent tie point. The average current carried is thus 75 per cent of the total and the duration is equal to the tie spacing divided by train speed. For a parallel feed wire with a higher self-impedance, the current split for the catenary will start at higher than 50 per cent so the average value would also be higher. The heating effect varies with the square of the current.

For several trains drawing power from a single catenary section, it is necessary to increase the current capacity of the total wire system. This may be done by using heavier contact and messenger wires, or by installing parallel feed wires on the catenary support poles to augment the lighter catenary. We will see later that catenary dynamics considerations indicate that the parallel feed system is to be preferred. The recommendations of the AREA for the calculation of current-carrying capacity are shown in Appendix F. The calculation is quite sensitive to assumptions on wind and sun conditions since annealing at high temperatures is the constraint. Calculations for average conditions reveal that a single 2/0 copper feed wire (or its equivalent) will increase the capacity of the catenary system to approximately 830 amperes, and that dual 2/0 copper feed wires will increase the capacity to approximately 1,120 amperes. See Table 3.1 for other variations. Wire spacing and location relative to the ground plane will affect the mutual impedance, and hence the current division between wires, thereby modifying the current capacity of the system to some extent. Although the 100 mm^2 contact wire is used by some jurisdictions, the preferred contact wire for Canada would be the standard 4/0 wire gauge.

The total required catenary current capacity, including a parallel feed system, will depend on line traffic, train spacing, grade characteristics, and substation spacing. The demands of individual trains are

unlikely to peak simultaneously. Detailed study of critical areas should be carried out during the design phase.

A reduction in the supply frequency will reduce the inductive impedance of the catenary system, and also increase the current-carrying capacity of individual wires.

TABLE 3.1

APPROXIMATE CURRENT CAPACITY OF CATENARY VARIATIONS AT 60 HZ*

Contact Wire	Messenger Wire	Feed Line	Current Capacity (amps)
100 mm^2	50 mm^2	-	500
100 mm^2	50 mm^2	1 of 80 mm^2	800
100 mm^2	50 mm^2	2 of 80 mm^2	1,100
4/0	1/0	-	530
4/0	2/0	-	650
5/0	3/0	-	810
6/0	4/0	-	1,020
4/0	1/0	1 of 2/0	830
4/0	2/0	1 of 3/0	1,020
4/0	2/0	1 of 4/0	1,040 current split**
4/0	1/0	2 of 2/0	1,120
4/0	2/0	2 of 3/0	1,380

* based on 4.7 A/mm^2 with 30 per cent contact wire wear, corresponding to the design limit at 37°C (ORE report A 1293RP31E).

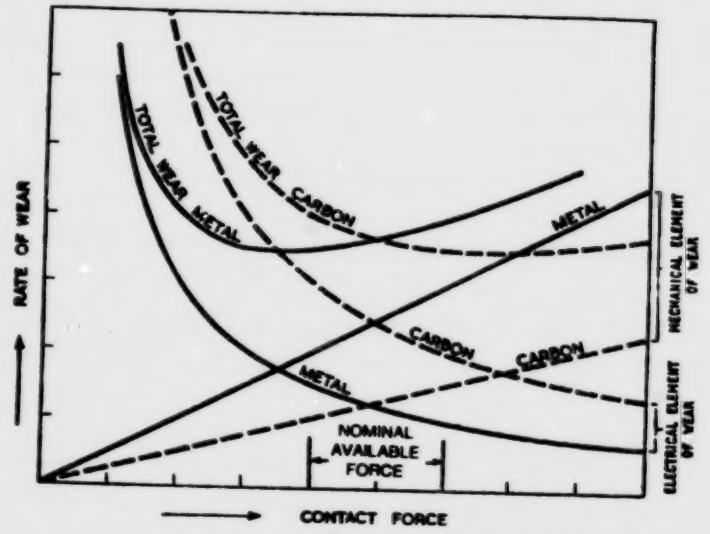
** current split - mutual impedance affects split, therefore placement is important

Increasing the supply voltage will have no effect on the catenary current capacity. Thus, a light catenary without parallel feed wires could supply the peak demand of four locomotives on a 50 kV supply system.

3.1.2 Catenary Dynamics

The pantograph, mounted on the locomotive or power car, must maintain continuous contact between the collector or contact strips and the contact wire of the catenary. It may be necessary to raise or lower the contact wire from its nominal elevation because of level-crossing constraints or clearance obstructions. Hence, the pantograph must be capable of following substantial but slowly changing wire heights, and it must follow the variation between the catenary support points (small, but rapidly changing). To meet the dynamic requirements, the design requires the minimum pantograph weight in keeping with structural requirements.

The contact force between the pantograph contact strip and the contact wire must be maintained within a limited range, 39 to 157 N (9.3 to 35 lbf),[2] under dynamic conditions. Figure 3.3 illustrates that too low a pressure results in excessive electrical wear, whereas too high a pressure results in excessive mechanical wear. If the upward force is excessive, the lift of the contact wire causes additional dynamic prob-



Source: Morganite, op. cit., p. 266

Figure 3.3 Effect of contact force on rate of wear of pantograph collectors

2 Ibid, p. 268.

lems for the catenary. The amount of permissible contact wire rise is determined by the weight of the wire, the tension in the wire, and by the arrangement of the supporting catenary system.

The normally available maximum force with present overhead systems is only just enough to ensure satisfactory contact for carbon collectors.

The chief benefit for carbon collectors, when operating within their acceptable limits, is the skin development on the contact wire, resulting in a substantial reduction in wire wear as compared with metal-to-metal surfaces. Also, carbon collectors result in lower electrical noise emission, greatly reducing radio and television interference.[3]

The current collectng capacity of carbon collectors is governed to a great extent by the heat generated at the lines of contact and the consequent temperature to which this heat raises the overhead contact wire. Table 3.2 indicates the steady current collecting capacity per contact which is possible at a contact force of 80 N (18 lbf). Additional current capacity can be achieved by increasing the number of contact strips. However, the increased uplift force on the contact wire to maintain the appropriate contact forces causes dynamic problems in the catenary. For areas requiring high current collection rates, some jurisdictions add a second contact wire to the catenary.

TABLE 3.2

STEADY CURRENT COLLECTING CAPACITY PER CONTACT

Grade Class	Amperes/Contact	
	Static	Moving
Hard carbon	50	100
Metal-impregnated	100	200

3 Ibid, p. 264.

It should be noted that the above figures are design values. Much larger currents can be collected when operating conditions are good (e.g. high humidity). Likewise, relatively short-period peak currents, such as at starting, may be much higher than the normal 'moving' current values shown in Table 3.1. The rate of carbon wear is directly dependent on the total current to be collected and on the effectiveness and stability of contact between carbon collector and wire.[4]

The contact wire is supported by a messenger wire to hold it in place parallel to the rail surface. An objective of the catenary design is to keep the height of the contact wire constant when the pantograph uplift force is applied. The vertical elasticity of the catenary varies between support points, becoming less stiff as centre span is approached. Thus, the design attempts to reduce the stiffness variation by including 'stitch wires' and/or elastic drop wires (which connect the contact wire to the messenger or support wire), and by building in a design sag in the contact wire which will offset the elastic variation.

For Canadian operations, multiple power units are required for both freight and express trains. The contact wire is pushed upward by the pantograph as the lead locomotive passes under the wire. The wire falls back into place under gravitational force, and, since it is a relatively undamped system, it vibrates (lashes up and down) for a period of time. A pantograph following closely behind the lead pantograph would be subject to a bouncing contact wire, and severe arcing would occur as the vibration makes and breaks the contact. The contact wire vibration will damp out in time, and hence, it is possible to calculate the necessary separation between two pantographs for a given train speed, or alternatively, the maximum train speed for a given pantograph separation.

One possible method of avoiding the dynamic problems of a tracking pantograph would be to use only a single pantograph for each train. However, the current flow required for a 9.5 MW train on a 25 kV system would require a double contact strip pantograph, and would introduce

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4 Ibid, p. 269

additional uplift forces on the catenary, with consequent dynamic complexities.

The 12.5 kV dc alternative would increase the number of contact strips to four, with even greater dynamic complexities. Transfer of power between locomotives would also add design and operating complexities.

The alternative is to design the catenary to provide a high critical speed, and to operate multiple power units with the necessary separation distance. The design details are presented in Appendix E.

To improve the dynamic response of the catenary and thereby minimize electric arcing at the contact-shoe/contact-wire interface, the following factors should be considered:

- wire tensions should be as high as possible
- wire mass should be as low as possible, in keeping with (1)
- span length should be decreased as much as is economically possible
- multiple unit pantographs must be separated by as large a distance as possible.

The selection of contact and messenger wire materials will affect the values determining the critical frequency of the catenary and hence the maximum speed of a multiple pantograph train. There is a trend in Europe to move to the cadmium-copper wire materials to gain increased tensile strength. A cadmium-copper alloy, such as SAE C16200, has a tensile strength of 450 mPa. This may be compared with standard copper wire, such as alloy C10200, with a tensile strength of 220 mPa, and bronze wire at 350 mPa. The electrical resistivity of the cadmium-copper wire is 12 per cent higher than that of the copper alloy, but in other respects the alloys are similar.

Power line design criteria do not permit tensile stresses exceeding 60 per cent of the quoted value. Thus, because of the higher tension possible, the cadmium-copper wire may be stressed to 270 mPa, while the copper wire may be stressed to only 132 mPa.

The density of the cadmium-copper wire is 0.6 per cent less than that of the copper wire. Thus, the dynamic characteristics of a cadmium-copper catenary is better than that of the all-copper catenary.

3.1.3 Wire Height

The wire height, and hence the mast height, affects the bending moment imposed on the masts by the wind load. Also, the wire height affects the pantograph width required, and hence the clearance diagram required.

The bending moment imposed by the wind, and by the wire tension on curve and tension masts, is a direct function of the wire height above rail. Thus, mast weight, and hence cost, may be affected by the choice of wire height.

The locomotive will roll and sway as it progresses along a track, as the result of track alignment, side bearing tilt, and spring deflection. In addition, the higher wire will require a longer pantograph arm, encouraging increased pantograph swing. Table 3.3 illustrates the effect of these factors on the active pantograph width required.

The numbers shown in the table are for illustrative purposes only. They may vary with specific situations and indeed they may form a basis for maintenance specifications. The probability of the simultaneous occurrence of all the components is quite low, but if it does occur, the locomotive pantographs no longer will supply power. Simple aggregation of the components results in unacceptably wide pantographs. However, regardless of the assumptions made, the required active pantograph width will increase with wire height. The locomotive design must consider the costs of reducing the magnitude of the individual factors affecting pantograph width.

The increased tension of the cadmium-copper catenary system results in reduced wire sag, reducing the overall depth of the wire system. This in turn reduces the mast height required to achieve a given contact wire height. It also reduces wind blowoff, reducing the need for a wider pantograph.

TABLE 3.3

EFFECTS OF LOCOMOTIVE BODY ROLL FOR A CLASS 6 TRACK

	Height Above Rail 19'0"	Height Above Rail 22'0"	Height Above Rail 25'0"
Lateral truck alignment	1.00	1.00	1.00
Side bearing tilt, 0.5"	1.57	1.87	2.17
Springs - 1" difference in height	3.89	4.50	5.11
Bolster swing neglected rails - 0.5" difference in height	2.02	2.34	2.65
Pantograph swing	1.88	3.00	4.12
Total	10.36	12.71	15.05
3" unbalanced superelevation	12.11	14.02	15.93
	22.47	26.73	30.98
Allowance for wire stagger	10.00	10.00	10.00
	32.47	36.73	40.98
Active pantograph width (in.)	64.94	73.46	81.98

Source: FRA-ONECD-75-5, North-East Corridor Report, August 1975, US/DTR-651-75 R005 ENG(BK), by Bechtel Inc.

The wire height and supply voltage affect the vertical load gauge. The horizontal load gauge and clearances affect the mast setback.

Table 3.4 illustrates the contact wire height for a 21'0" load gauge (6.40 m). The Northeast Corridor used a specification of a 21'0" (6.40 m) minimum wire height, with 21'9" (6.63 m) maximum. At 25 kV, the indicated load gauge of the Northeast Corridor is 20'0" (6.10 m).

TABLE 3.4

WIRE HEIGHT, FOR 21'0" LOAD GAUGE

	Normal	Minimum
50 kV	24'3"	22'7.5"
25 kV	23'4.5"	21'11.5"
12.5 kV	22'11.25"	21'7.5"

Increased mast setback required to ease snow clearing will increase the bending moment effect of wire weight and ice load.

3.1.4 Phase Breaks

In the study, it was assumed that adjacent catenary sections in the industrial frequency systems would be fed from different phases of the utility three-phase supply. This requires that a phase break -- an insulated section of catenary -- be provided for each section. Each catenary section would require a supply substation, and hence, the number of phase breaks would match the number of substations. If the utility system fault capacity was sufficiently high, it might be possible to feed some adjacent sections from the same phase, reducing the required number of phase breaks.

A locomotive traversing a phase break would suddenly be isolated from the power supply, and equally suddenly be re-energized. Severe arcing, and mechanical stresses, could occur. The practice is to locate phase breaks such that the train can coast through them. Prior to entering the phase break, the electrical load is reduced to a minimum, with reapplication of the power demand after the pantograph has traversed the phase break.

With multiple pantographs, the operation of power reduction and reapplication at each phase break becomes more complex. This is particularly true if trains are to use robot power. Train action could be quite severe.

Although the power reduction and pickup could be automated, we are not aware of a successful application. This should be studied further, to develop the appropriate criteria for the location of phase breaks. The increased spacing of substations, and hence the reduction in the number of phase breaks, favours the 50 kV system.

3.1.5 The Implications of the Physical Constraints

A typical catenary, using a 4/0 contact wire and a 1/0 messenger wire, would meet the current demand required by a 9.5 MW train, at either 25 or 50 kV. However, to meet the current demand of a single heavy train with a 12.5 kV supply, the current capacity of the contact and messenger wire assembly must be roughly 1060 amps, requiring a heavier catenary system. The additional size and weight of the catenary would have substantial effects on both the dynamics and cost.

The locomotive consist of a heavy train, operating on 12.5 kV, would require four pantographs contact strips to provide sufficient current collection capacity. Although possible on a single pantograph, the effects on the dynamic compliance of the pantograph-catenary system are severe. The 25 kV system would require only two contact strips, easing the dynamics problems. On a 50 kV system, a single pantograph contact strip could provide the necessary power for all train configurations.

As the 12.5 kV dc option has other technical limitations which must be overcome, the difficulties outlined above for the 12.5 kV system were not considered in the cost evaluation or the 12.5 kV system.

Based on a typical cadmium-copper catenary, and using the RC4 electric locomotive as an example (at 15.59 m, or 51 ft, in length, the RC4 is a compact locomotive), dynamic analysis of the catenary system suggests that a multiple locomotive consist would encounter no current collection problems, due to catenary dynamics, for speeds of less than 72.5 km/h (45 mph). While this speed limit might be acceptable for some bulk-goods trains, it is not acceptable for most other trains. Fortunately, a simple increase in pantograph spacing would proportionally increase the critical train speed. Thus, a separation of 23.65 m (77.6 ft) would permit express train speeds of 110 km/h. This increase in pantograph spacing might be achieved with longer locomotives, or by asymmetric mounting of the pantograph on the locomotive. The catenary

span might be reduced to improve the catenary dynamics, reducing this constraint on pantograph spacing. However, the 63 m span is judged to be close to the economic minimum.

If a passenger train must operate with multiple pantographs, they should be at least 43.0 m (141.1 ft) apart. A pantograph on alternate cars, or at opposite ends of the train, would meet this restriction.

3.1.6 Relative Catenary Costs

A lower voltage will permit lower-cost insulators and a lower wire height which will permit a lower-cost mast, but the relative effect on total catenary costs is not dramatic. For this study, 25 kV was given a seven per cent saving and 12.5 kV a ten per cent saving over 50 kV for the same current capacity. Some of the options required additional conductors which increased their cost.

For costing the 50 kV catenary, a 4/0 copper contact wire, 2/0 ACSR messenger wire and 4/0 ACSR return wire were used for each track. The estimated total cost was $80,600 per track-km. In the corridor region, the use of booster transformers was assumed as an EMC measure. The spacing of these booster transformers was assumed to be 4.8 km for the 50 kV case and was adjusted for the other cases to give the same maximum Ampere-km-Hz product for a single train load. The total cost of each booster transformer was estimated to be $25,000. The impedances of the catenary systems were calculated by Carson's formula using data and methodology which were developed by Driver.[5] The use of booster transformers in the corridor forces the return current to flow in the return conductor, rather than the lower impedance rail and earth return, and also offers a series impedance. The result is a much higher catenary impedance in this region. The impedance and costs of the various alternatives are summarized in Table 3.5.

3.2 SUBSTATION AND UTILITY FEED

There are two elements to substation sizing -- the necessary spacing and the necessary capacity. The former is relatively inflexible and

5 Driver, J.B., Track and Trolley Impedances for Electrified Railroads, M.Sc. Thesis, Illinois Institute of Technology, January 1963.

TABLE 3.5

CATENARY COST AND IMPEDANCE VALUES

Case	Catenary Type (each track)	Double-Track Impedance		Cost	
		No Booster Transformers (ohm/route-km)	With Booster Transformers (ohm/route-km)	No Booster Transformers (K$/route-km)	With Booster Transformers (K$/route-kim)
50 kV, 60 Hz	C - 4/0 CU M - 2/9 ACSR R - 4/0 ACSR	R = 0.107 X = 0.293	R = 0.161 X = 0.428	161.2	171.4
25 kV, 60 Hz	C - 4/0 CU M = 2/0 ACSR R - 4/0 ACSR	R = 0.107 X = 0.29	R = 0.164 X = 0.44	150.0	171.2
25 kV, 25 Hz	C - 4/0 CU M - 2/0 ACSR F - 2/0 ACSR R - 2/0 ACSR	R = 0.078 X = 0.105	R = 0.146 X = 0.140	159.4	169.2
12.5 kV, dc	C - 4/0 CU M - 2/0 ACSR F - 2/0 ACSR R - 300,000 MCM ACSR	R = 0.103	n/a	155.5	n/a

C - contact wire; M - messenger wire; F - feed wire; R - return wire

should be evaluated on the basis of conditions existing near the end of the system economic life, while the latter can be increased with relative ease and may be sized initially on a much shorter time frame.

3.2.1 Substation Spacing

The location of substations is dependent on many complex factors. However, the maximum spacing is restricted by voltage regulation at the locomotive, which is dependent on the relative position and power requirements of trains traversing the line; these factors are stochastic in nature. As a consequence of these stochastic elements, one must consider what is an acceptable frequency of mishap -- in this case undervoltage at the locomotive.

The present evaluation of alternative distribution systems will restrict substation spacing on the basis of the following criteria:

- on the basis of the expected traffic density in year 30 and under normal operations, the voltage regulation at the locomotive will be such that the continuous rating will only be constrained by inadequate regulation on the average of once every two months

- with the same traffic loading, but in an emergency situation where one substation is shut down, all trains must be able to traverse the 'downed' section at a speed of 25 km/h, without tripping out on undervoltage for conditions expected to occur four days out of five.

It should be noted that if these constraints are not met, the consequences are not drastic. In the first situation some loss in performance would be briefly experienced and in the second situation a train might have to wait for other trains to clear the 'downed' section before it proceeds. It may be desirable to relax any one of these design constraints in a detailed site-specific study. The intention here is to apply a reasonable set of criteria consistently to each alternative. The relative cost relationships between alternatives will be much less sensitive to changes in these criteria than are the actual costs.

The voltage regulation requirement at the locomotive is taken as the AREA recommended values of 0.8 for continuous power and 0.7 for shutdown. A discrete probability density function, estimated on the basis of having several independently dispatched train types traversing the line at a specified average speed and average power demand is used to determine the nature of the electrical load at the substation. The method of determining this probability density function is described in Appendix A.

The probability density function associated with the 'mountain' case at year '30' traffic levels is illustrated in Figure 3.4. For a track interval of 39 km, one can expect to see a simultaneous load of four trains once every two months on average. An additional two trains might be expected in the adjacent track section. The location of the loads was skewed to the far end of the substation feed point to determine the voltage regulation. The locations associated with the above case are illustrated in Figure 3.5. The voltage at each locomotive was

determined by a Gaussian iterative algorithm[6] and the whole process was repeated as necessary with reduced substation spacing until the voltage regulation criteria were met.

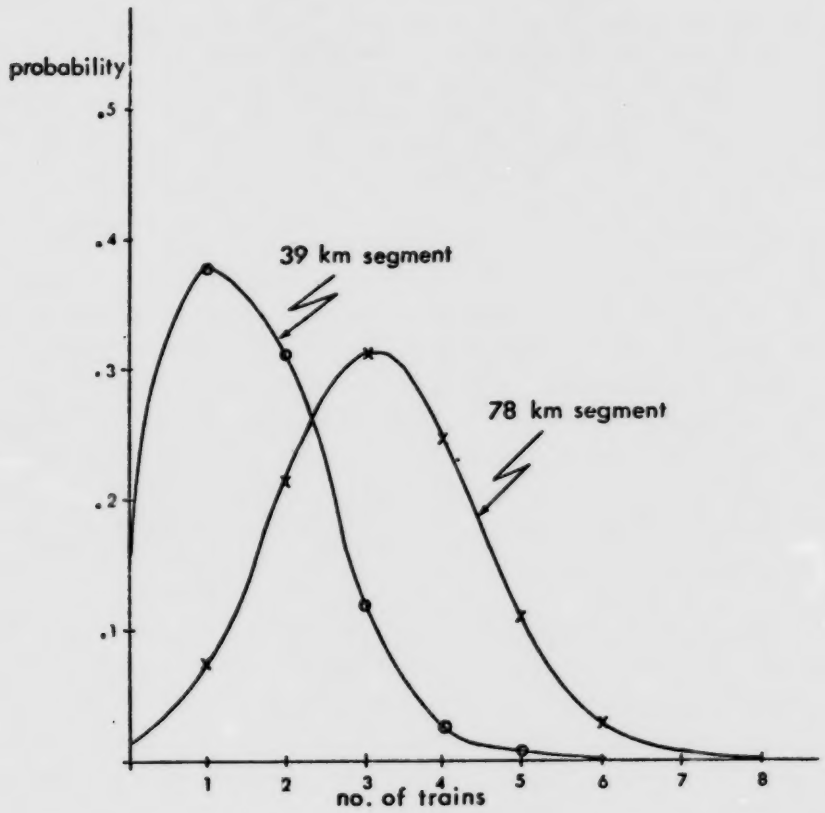


Figure 3.4 Probability of coincident trains on a track segment

The substation spacing for each region/alternative combination is shown in Table 3.6. For all regions, the 50 kV alternative permits the longest spacing and the 25 kV, 60 Hz alternative is in the order of

6 For a detailed description of this and other load flow algorithms, see for example: Stagg, G.W., El-Abiad, H.A., Computer Methods in Power Systems Analysis, McGraw-Hill, 1968.

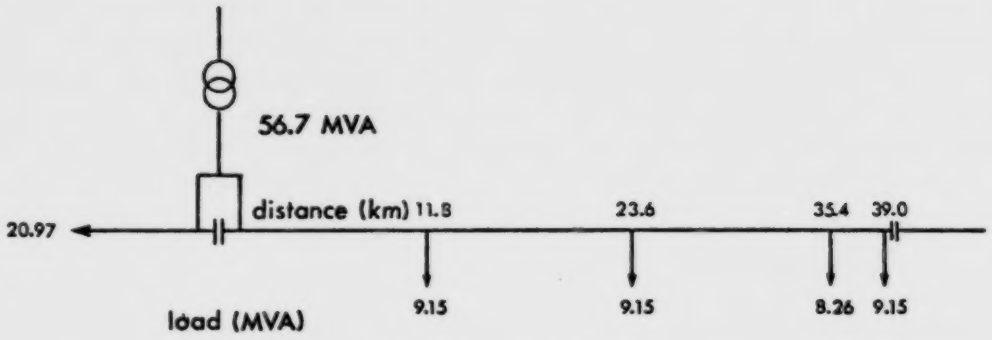


Figure 3.5 Train locations for voltage regulation criteria (mountain case)

one-third the 50 kV spacing. The lower frequency in combination with a double-end feed arrangement permits about a two-and-one-half-fold increase for the 25 Hz case over the 60 Hz option at the same voltage. The dc option with a double-end feed also has a longer spacing than the 25 kV, 60 Hz option, even though the dc feed is at one-half the voltage.

TABLE 3.6

SUBSTATION SPACINGS
(km)

	Region		
Case	Mountain	Prairie	Corridor
50 kV, 60 Hz	78	87	74
25 kV, 60 Hz	26	32	26
25 kV, 25 Hz	68	81	65
12.5 kV, dc	36	48	45

Comparing the regions, the prairie region permits the longest substation spacings because the lower tonnage and faster trains result in

a lower total demand for a given track length. The corridor region uses booster transformers which increase the catenary impedance by 50 per cent but the substation spacing is about the same as the mountain region. This is because the substation power demand is lower in the corridor -- train powers are lower, tonnage is lower and the higher speeds reduce the probability of seeing large numbers of trains on a track segment.

3.2.2 Connection Types Used

The type of connection made and the equipment used at the substation are influenced by the requirements of the electrical utility. A double-end feed connection, as illustrated in Figure 3.6, permits longer substation spacing but was limited in application to those alternatives which isolated the railway catenary from the utility distribution system. In the cases which involve a direct tap to the utility grid, there are disadvantages associated with the double-end feed which may offset the potential of increased substation spacing. The connections made at railway substations are usually alternate phases so that the net load imbalance to the utility is reduced. Thus, in the emergency situation, when one substation is down, the adjacent catenary sections would be of different phases, thereby precluding a double-end feed connection in that circumstance. If one desires to continue train movements in this situation, the substation spacing must be reduced significantly. In addition, the double-end feed can lead to large circulating currents in the railway catenary because the double-end feed provides a path for circulating currents in the railway catenary when the utility high-voltage system is unbalanced or suffering faults. Special protection is needed to limit these circulating currents and to isolate one end of the feed system in the event of a fault.

The double-end feed alternative warrants a more detailed investigation for site-specific studies. There may be areas where its advantages (of about double the substation spacing of the centre-feed arrangement) outweigh its disadvantages. However, as it may be applied to either 25 kV or 50 kV, its use should not significantly influence the relative outcome of the following analysis.

Figure 3.6 Double-end feed connection

The types of connections used in the alternatives which involved a direct tap to the utility are illustrated in Figure 3.7. The specific connection used is determined by the permissible load imbalance. The mitigating effects of the alternative connections on voltage imbalance at the utility connection is explained in more detail in Appendix B. Only the general effects are summarized below. A centre feed with a single transformer, which is the simplest and least expensive alternative, was used if the load imbalance was acceptable. The load imbalance associated with this connection is the total of the train loads on each side of the connection point. If this load exceeds the utility's limit, the next choice is an end-feed connection with two transformers connected to different phases. The load imbalance associated with this feed arrangement is dependent on the relative magnitude of the two loads connected. In relatively dense traffic conditions, this imbalance will be somewhat greater than one-half of the combined load seen by the centre-feed connection. The incremental cost associated with this second alternative is estimated to be 33 per cent of the centre feed choice.

If the load imbalance associated with this connection is still unacceptably high, the next choice is a Scott-connected transformer. This is a three-phase to two-phase connection which will present a balanced load to the three-phase system when a balanced load is applied to the two-phase system. In general, the voltage imbalance on the three-phase side is proportional to the load imbalance on the two-phase side. The incremental cost associated with this connection is estimated to be 40 per cent of the centre feed connection.

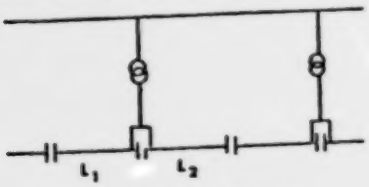
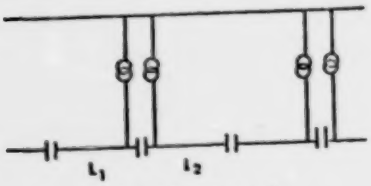
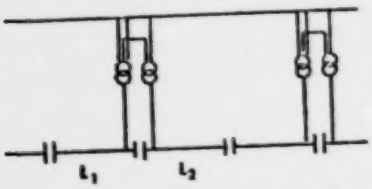
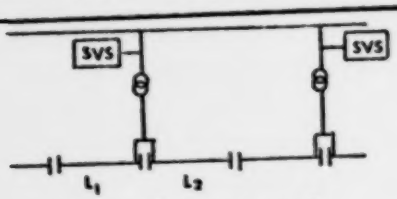
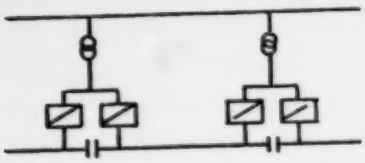
Type	Load Imbalance	Relative Cost
 Centre Feed	$L_1 + L_2$	1.00
 End Feed	$[(L_1-.5\ L_2)^2 + (.866\ L_2)^2]^{.5}$	1.33
 Scott Connected	$\text{abs.}\ \lvert L_1-L_2 \rvert$	1.40
 Centre Feed with Scalene Scott or SVS	0	1.5-2.4
 Double-end Feed with Frequency Converters	0	4.0-6.0 ac/ac 3.0-4.0 ac/dc

Figure 3.7 Substation connection alternatives

If the Scott connection presents an unacceptable load, several types of reactive load-balancing systems can be designed and used to compensate for any size of load. ASEA have installed primary load-balancing equipment in a railway application in South Africa and the JNR is considering a combined scalene-Scott connection and reactive load balancing system.[7] ASEA estimates the incremental cost of their system to be in the order of 150 SwK ($33 Cdn) per reactive kilovolt-ampere. However, this cost is quite sensitive to the desired tolerance around the 'target' imbalance. For example, the cost per reactive kVA of a single bank of 15 MVA reactive elements per phase would be less expensive than five banks at 3 MVA each but the variation in imbalance would be greater.

The scalene-Scott connection system appears to have a much lower incremental cost in situations of a relatively constant load power factor. However, cost details were not available so the primary load-balancing system was assumed for estimating purposes. For the conditions evaluated in this study, the substation cost increment was in the 70 to 140 per cent range.

As noted, the cost of load-balancing equipment, whether primary or scalene-Scott, is quite sensitive to the allowable variations in voltage imbalance, since the larger this is, the fewer the number of controlled banks of reactive elements. The costs used here are considered to be in the upper part of the possible cost range.[8] Lower costs would improve the relative position of 50 kV, since it has the longest substation spacing and would require voltage balancing measures to be taken before the other alternatives would.

The base cost of a 30 MVA 230/50 kV centre-feed, two-track substation was estimated to be $2.8 million. The relative costs of 25 kV and 50 kV at different power levels were taken from an ASEA estimate shown in Figure 3.8. Note that the relative cost of the railway substations

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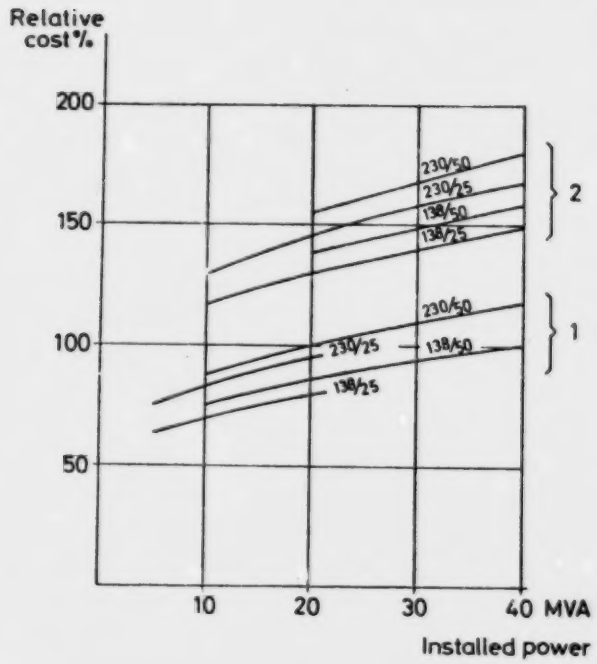
7 See Appendix B for details.

8 At the bottom end of the cost range for a primary load balance system, CPCS have estimated a cost of about $10 per reactive kVA for a single-arm breaker-controlled system in conjunction with the Cartier Railway demonstration project.



Source: ASEA Information Bulletin TB000-103E, April 1973, "A Comparison Between 50 kV and 25 kV a.c. as Supply Voltage for Railway Traction"

Figure 3.8 Relative cost of railway single-phase substations

would seem to vary on a somewhat less than proportionate relationship to substation capacity, owing to the relatively large cost component of site preparation, structures, controls, metering and other such costs which are not a function of installed power. The unit cost of a cycloconverter for ac/ac conversion (60 Hz to 16^2/3 Hz) was also an ASEA estimate -- one million SwK (220 K $ Cdn/MVA) in addition to the normal substation equipment. The cycloconverter is limited in application to areas of high utility grid density because of the subharmonics which it generates. In Sweden it is restricted to areas in which the load represents only 0.8 per cent of the three-phase short circuit capability. In areas where this limit is exceeded, a more expensive ac/dc/ac converter, having a ten per cent short-circuit limit, is used. We have estimated the cost of this method to be $270/kVA and the cost of an ac-to-dc converter to be $50/kVA.

The options which involve the use of converters must be rated to handle the full momentary loading of the system, whereas the direct tap alternatives can withstand significant overloads for short intervals and have a much lower continuous power rating than the converter options.

An autotransformer feed system such as is used on the recent Paris-Lyon electrification was not evaluated in detail because of the high cost reported in two previous studies.[9,10] The additional high-voltage feed wire would also lead to clearance problems and the 7 to 15 km spacing would mean that autotransformer stations would have to be installed inside a number of long tunnels which exist on CP Rail's mountain line. The type of coaxial feed system which has been used in special situations in Japan was also not evaluated in detail because of the very high cost for the cable as reported by the Japanese National Railway.[11] Both of these systems are variations of the industrial frequency alternatives. If detail studies show them to be effective in site-specific applications, they may be applied at a compatible voltage.

3.2.3 Utility Feed Lines

The cost of utility feed lines to the railway substations will vary more on a site-specific basis than will the cost of the substations. The average feed distance for each of the three regions was estimated from the National Energy Board Map of Principal High-Voltage Transmission Lines in Canada. The corridor region has a dense distribution network and in many areas transmission lines run parallel and in close proximity to the rail lines. The Prairie region has a sparser distribution network, but the principal lines again are in close proximity to

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9 Avery, R.M., "Various AC Traction Power Feeding Systems Which Mitigate EMI and Their Relative Costs," Proceedings of Symposium on Railroad Electromagnetic Compatibility, May 1980, U.S. DOT Report No. FRA/ORD-80/46.

10 Gibbs and Hill Inc., Electrification Feasibility Study performed for CONRAIL, November 1979.

11 Maekawa, N., "Alternating Current Feeding System Using Coaxial Cable," Japanese Railway Engineering, Vol. 16, Nos. 3 and 4, 1976.

the railway main lines. The mountain region has some segments of track which parallel transmission lines and others which are quite remote from principal lines. The average feed distances which have been estimated are considered to be very rough approximations.

The cost of transmission lines was based on a Manitoba Hydro estimate for its 230 kV lines, in the Prairie region, with a 50 per cent increment in the Mountain region to reflect the more rugged terrain conditions. The estimated average conditions of feed length and cost are shown in Table 3.7.

TABLE 3.7

UTILITY FEED COSTS

Region	Average Feed Distance (km/substation)	Average Cost (K$/km)	Total Cost (K$/substation)
Mountain	20	60	1,200
Prairie	10	40	400
Corridor	10	60	600

3.3 COMPARATIVE UNIT COST OF SUBSTATIONS

The implications of the preceding analysis and cost estimates for the cost of substations for each alternative is summarized in Table 3.8.

The effects of the utility imbalance limit are evident in the table. The corridor region, which requires no mitigating measures, demonstrates a significant cost saving for the 50 kV case, even though the substation spacing was 5 per cent shorter. The 20 MVA limit in the mountain region led to an end-feed connection for the 50 kV case, forcing 33 per cent cost increase, and the 10 MVA limit led to a Scott connection for the 50 kV case, forcing a 40 per cent cost increase. The 25 kV, 60 Hz option, on the other hand, could use the centre feed connection at the 20 MVA limit but requires an end-feed connection with a 33 per cent cost increase at 10 MVA.

TABLE 3.8

SUBSTATION AND (UTILITY FEED) COST
(K$/route-km)

Case	Region				
	Mountain (max.) (10 MVA) (load) (imbalance)	Mountain (max.) (20 MVA) (load) (imbalance)	Prairie (10 MVA) (imbalance)	Prairie (20 MVA) (imbalance)	Corridor
50 kV, 60 Hz	70.1 (15.5)	50.63 (15.5)	51.15 (4.6)	40.86 (4.6)	37.7 (8.1)
25 kV, 60 Hz	116.6 (46.5)	87.6 (46.5)	90.36 (12.5)	67.79 (12.5)	87.6 (23.3)
25 kV, 25 HZ	220.7 (17.7)	220.7 (17.7)	160.0 (4.9)	160.0 (4.9)	156.0 (9.3)
12.5 kV, dc	121.2 (33.8)	121.2 (33.8)	89.6 (8.3)	89.6 (8.3)	87.5 (13.3)

3.4 THE RELEVANT OPERATING COSTS

3.4.1 Utility Energy Charges

The relevant energy charges are only those which are associated with the losses in the candidate systems. The train energy at the pantograph is essentially the same for all of the alternatives. The principal losses are the I^2R losses in the catenary and the power loss in the diodes and SCR's of the converters.

The catenary losses are estimated to be two per cent for the 50 kV case in the mountain regions and three per cent in the corridor where booster transformers are used. The losses of the other cases will be increased by the inverse of the voltage ratio squared but some of the alternatives have extra conductors which lower the R value. The net

effect for the four alternative systems is shown in Table 3.9. Also shown in the table are the loss estimates associated with the substation equipment. The converter substations are estimated to have an additional no-load loss of 300 MW-h for the ac/ac case and 100 MW-h for the ac/dc case.

TABLE 3.9

PER CENT ENERGY LOSSES UNDER LOAD

Feed System	Catenary Losses		Substation Losses	Total	
	Corridor	Other		Corridor	Other
50 kV, 50 Hz	3	2	2	5	4
25 KV, 60 Hz	12	8	2	14	10
25 kV, 25 Hz	9	6	12	21	18
12.5 kV, dc	18	18	6	24	24

To express the losses on a unit distance basis, the annual train energy requirement has been estimated on the basis of sample train simulation runs. The on-load losses are a direct percentage of this, while the no-load losses must be divided by the substation spacing. The total energy consumptions derived for the first-year traffic levels and the cost of the associated losses are shown in Table 3.10.

3.4.2 Utility Demand Charge

The estimates of the demand charge imposed by the utility are based on 15-minute integrating meters located at each substation with a monthly charge of $5/kW for the maximum 15-minute average reading over the month. To estimate the average magnitude of the maximum 15-minute power demand, the expected load on a daily basis was determined by the

TABLE 3.10

ENERGY LOSSES BY REGION

Region	Energy Charge ($/MW-h)	First Year Locomotive Energy Consumption (MW-h/km)	Cost of Losses (K$/km) 50 kV, 60 Hz	25 kV, 60 Hz	25 kV, 25 Hz	12.5 kV, d.c.
Mountain	14	1,066	0.60	1.49	2.72	3.25
Prairie	12	810	0.39	0.97	1.75	2.33
Central	14	730	0.41	1.02	1.84	2.45

method described in Appendix A. Since the highest reading on a monthly basis is used for billing purposes, the average monthly billing load is higher than the average daily load. The average train load found in this manner was reduced by an average load factor of 0.9 and the losses associated with the relevant distribution system were then added to arrive at the final metered demand. Since the demand charge is based on power at the substation rather than energy, the catenary energy losses which were discussed in the previous section must be modified by the relative catenary feed lengths to get the power effects. The resulting power increments are shown in Table 3.11.

While the energy consumption will grow in direct proportion to traffic growth, the metered power demand does not. The estimated power demand associated with the initial and year-thirty traffic levels is shown in Table 3.12.

3.4.3 Substation Maintenance Charges

The annual maintenance costs associated with only the substations are considered. The differences in catenary costs are considered to be insignificant for the alternative systems. The maintenance costs are

TABLE 3.11

POWER DEMAND MULTIPLIER DUE TO LOSSES

Case	Region		
	Mountain	Prairie	Corridor
50 kV, 60 Hz	1.04	1.04	1.05
25 kV, 60 Hz	1.047	1.049	1.06
25 kV, 25 Hz	1.173	1.176	1.20
12.5 kV, dc	1.15	1.160	1.168

TABLE 3.12

SUBSTATION DEMAND READINGS - YEAR 1 AND (YEAR 30)
(MW)

Case	Region		
	Mountain	Prairie	Corridor
50 kV, 60 Hz	28.45 (40.44)	21.44 (27.3)	20.41 (27.22)
25 kV, 60 Hz	15.83 (19.60)	11.6 (15.23)	9.54 (13.13)
25 kV, 25 Hz	29.56 (43.07)	23.16 (29.12)	21.6 (30.06)
12.5 kV, dc	19.91 (25.67)	14.89 (22.96)	15.48 (21.86)

estimated as $28,000 per annum for the basic substation and an additional two per cent of capital cost for converters or load balancing equipment where used. The resulting charges on the unit distance basis are illustrated in Table 3.13.

TABLE 3.13

ANNUAL SUBSTATION MAINTENANCE COSTS
($/km)

Case	Region		
	Mountain	Prairie	Corridor
50 kV, 60 Hz	361	322	377
25 kV, 60 Hz	1,085	875	1,085
25 kV, 25 Hz	3,985	2,854	2,686
12.5 kV, dc	1,694	917	1,130

3.5 CLEARANCE COSTS

The installation of an electrical conductor above the rail requires that a sufficient clearance be maintained to any nearby grounded objects so that arcing does not occur. The required clearance increases with line voltage so the cost of civil reconstruction will also increase with voltage. A copy of the AREA clearance recommendations are included in Appendix D.

To meet these recommendations, the contact wire must be at the appropriate static clearance above the highest desired operating load height, the messenger and any other feed wires must have the appropriate static clearance from any overhead structures and the locomotive pantograph must have the appropriate passing clearance from any overhead structures.[12] Because the locomotive experiences lateral movement and body roll, the active pantograph width is larger than its physical width and the active width also increases with the height of the pantograph. Table 3.3 presented in Section 3.1 illustrates the components of the active pantograph width.

12 If the locomotive frequently stops at the overhead structure then the static clearance should be used.

The AREA-recommended clearance diagrams for bridges and tunnels are shown in Figure 3.9 superimposed on the voltage clearance recommendations discussed previously. The bridge and tunnel heights are 6.7 m (22 ft) and 7 m (23 ft) respectively at the track centre line. The cost associated with the civil reconstruction required at overhead obstructions will be site-specific and it is not possible to use a system average cost with any confidence. For most overhead bridges one would expect the cost function to resemble that shown in Figure 3.10. For low voltage, the existing clearance may be satisfactory and thus no modification is necessary. This zero cost region is depicted by segment 'a' of Figure 3.10, and the situation is illustrated by the 25 kV, 5.94 m load height, tunnel combination of Figure 3.9. With increasing voltage, the height and width clearance requirements increase and will eventually lead to a point where the messenger wire or the outside tips of the pantograph lead to clearance problems, such as illustrated by the 25 kV, 5.94 m load height, bridge combination of Figure 3.9. In these cases, relatively low cost means can be employed. Bridge trusses may be wrapped with insulation above the messenger wire or a tunnel roof may be scarfed at the appropriate point. In these situations there will be a fixed cost of track possession time, assembling and transporting work crews and renting equipment. The variable cost of wrapping 20 cm of truss rather than 10 cm or scarfing 10 cm of tunnel rather than 5 cm would be relatively insignificant. The associated cost is represented by segment 'b' of Figure 3.10. As voltage or the desired load height increases, one gets to the point where major modifications are necessary, tracks must be lowered, tunnel roofs, overhead trusses and overhead bridges must be raised or replaced. This situation is illustrated by both 25 kV and 50 kV for the 6.4 m load height situation of Figure 3.9. Here again, the fixed cost will generally overshadow the differences of achieving a 20 cm clearance or a 40 cm clearance. This situation is represented by region 'c' of Figure 3.10.

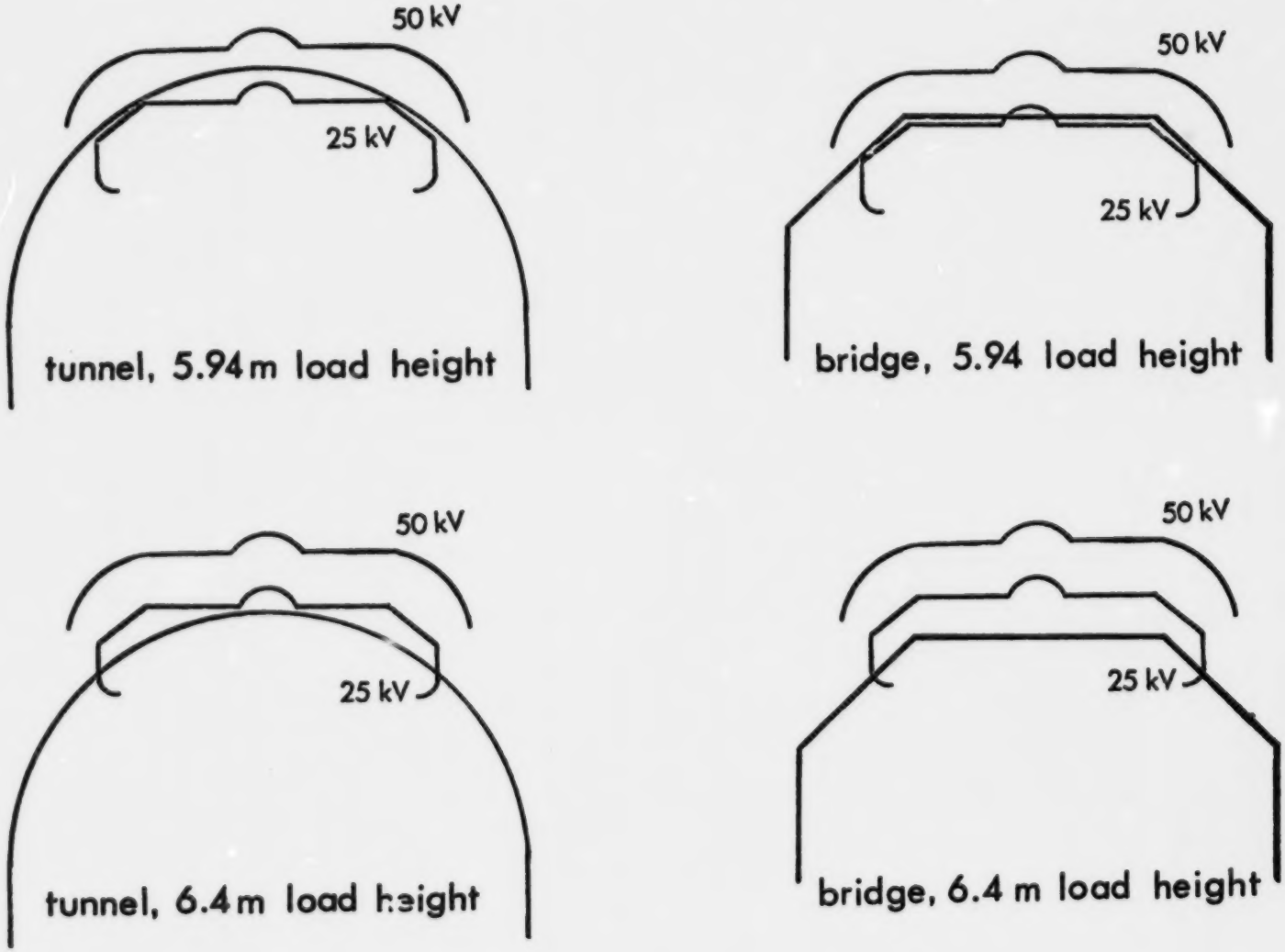


Figure 3.9 Tunnel and bridge clearance obstructions

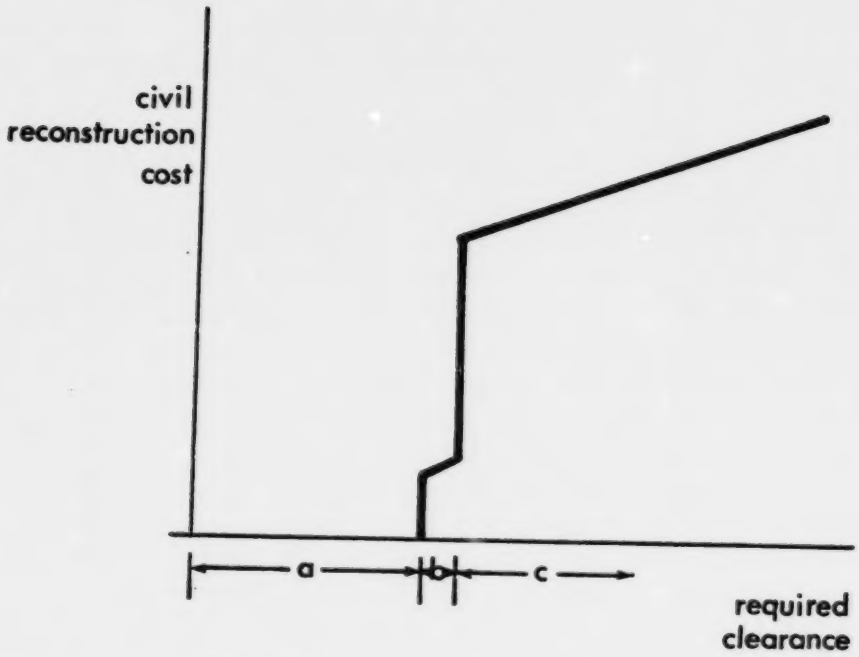


Figure 3.10 Estimated shape of the civil reconstruction cost function

On the basis of the above cost functions one could say that 25 kV would exhibit a significant clearance cost saving in association with a 5.94 m (19.5 ft) load height but a much reduced saving for any higher load heights.

It is evident that the voltage decision and the maximum load height decision must be addressed simultaneously, with the clearance cost savings compared with the present value of future opportunity costs in lost contributions to fixed costs from shipments of excess height. The data required for this decision are not presently available.

Table 3.14 gives an indication of the frequency of possible clearance obstructions in the three identified regions for the CN main line system. Table 3.15 illustrates the relative occurrence of regions A, B and C from the cost function illustrated previously in Figure 3.10. Taking the Mountain region as an example, a 5.94 m load height would

TABLE 3.14

NUMBER OF OVERHEAD CLEARANCE RESTRICTIONS (CANADIAN NATIONAL)*

Area	5.8m	6.55m	6.7m	6.86m	7.01m
Montreal-Toronto	70	65	60	53	18
Winnipeg-Edmonton	16	15	13	11	-
Edmonton-Vancouver:					
bridges & snowsheds	37	36	35	34	0
tunnels	29	29	24	23	0
(length in feet)	19,971	19,971	14,328	12,658	0

* measured at the track centre-line

TABLE 3.15

OVERHEAD CLEARANCE OBSTRUCTIONS FOR THE CN MAINLINE SYSTEM
(bridges/100 route-km)*

		5.94 m Load Height			6.4 m Load Height		
Region	Case	Cost Region A	Cost Region B	Cost Region C	Cost Region A	Cost Region B	Cost Region C
Corridor:	25 kV	9.7	1.3	1.8	3.3	-	9.5
	50 kV	-	-	12.8	-	-	12.8
Prairie:	25 kV	0.8	0.2	0.3	-	-	1.3
	50 kV	-	-	1.3	-	-	1.3
Mountain Bridges:							
	25 kV	2.7	0.1	0.2	-	-	3.0
	50 kV	-	-	3.0	-	-	3.0
Mountain Tunnels:*							
	25 kV	-	308	178	-	-	486
	50 kV	-	-	486	-	-	486

* tunnels are metres/100 km

mean no modifications and most of the tunnels would only require scarfing at 25 kV. However, if a 6.4 m load height is required, then all bridges and tunnels would require major modifications at 25 kV. With 50 kV, major modifications would be required for either load height.

The above data are based on measurements from the track centre-line. Table 3.16, which is a summary of 1975 data for selected Canadian main-line railways, illustrates the rate at which vertical clearances are reduced for deviations from the track centre-line.

TABLE 3.16

RAILWAY VERTICAL CLEARANCES AT DIFFERENT LOAD WIDTHS
(1975)

Rail Segment	Load Width 11'6"	Load Width 7'0"
Canadian Pacific:		
Vancouver to Calgary	14'0"	18'6"
Calgary to Winnipeg	19'3"	20'0"
Winnipeg to Toronto	18'9"	19'9"
Canadian National:		
Vancouver to Edmonton	16'0"	19'0"
Edmonton to Winnipeg	18'0"	20'6"
Winnipeg to Toronto	17'0"	18'9"
Toronto to Montreal	16'6"	19'9"

Oversize loads might be transported along electrified lines by diesel-powered locomotives. De-energization of a 25 kV catenary would permit an increase in load gauge of 8.5" (21.6 cm). Similarly, de-energization of a 50 kV catenary would permit an increase in load gauge of 17.0" (43.2 cm).

3.6 ELECTROMAGNETIC COMPATIBILITY

As with clearance costs, the costs associated with attaining EMC cannot be identified in a study of this size. However, the relative contribution of the different distribution systems can be compared for the magnitude of the generated magnetic fields, which are the source of the problem. Identifying the physical quantities of affected wayside conductors and the cost of mitigating the induced voltage in those conductors are large and difficult tasks. Our focus is thus on the relative contribution at the source for the alternate systems.

The traction return currents, which must be partially carried by the rails, create a problem for existing track circuits, regardless of the power feed system chosen. The difference in the cost of attaining compatibility with track circuits for the different feed systems is estimated to be insignificant. The power system induction effect on wayside conductors does affect the cost of attaining EMC, and hence it will be analyzed.

Current flowing in a conductor produces a magnetic field which will induce a voltage in parallel conductors which is proportional to both the magnitude and frequency of the current, and to the mutual inductance between the conductors. This voltage may be expressed as:

$$E_2 = j\, 2\pi f M_{12} I_1 \ell$$

where: f = frequency

M_{12} = mutual inductance between the two conductors

I_1 = current flowing in conductor 1

ℓ = length of parallel exposure.

The power-conditioning units on electric locomotives generate harmonic currents, which reflect back into the electrical distribution system. These harmonic currents induce audio frequency currents in parallel conductors. If a telephone wire pair is present and the resistance to

ground of the two conductors is not exactly the same, a voltage difference results across the two wires, producing noise in the receiver.

In addition to induced noise, the fundamental current can induce significant voltages-to-ground, which create safety hazards for employees working on conductors paralleling the railway catenary. The most commonly used standard for this is the International Consultative Commission on Telephone and Telegraph Systems (CCITT) standard which recommends maximum induced voltages-to-ground of 60 V and 430 V under normal and fault conditions, respectively.

The dc alternative is the only one which has zero frequency and therefore cannot induce hazardous voltages from the fundamental currents. However, the dc system is more prone to arcing at insulators, which can produce very large noise currents, and the power-conditioning unit at the locomotive may generate a harmonic current equivalent to that of a 60 Hz locomotive. Also, the earth return currents can lead to corrosion of buried steel such as pipelines, if countermeasures, such as cathodic protection, are not taken.

For the ac systems, the frequency, current and feed length all vary with each alternative. The relative effects at the fundamental frequency are illustrated in Table 3.17 for two of the regions. Two measures are used for the comparison. The first measure is the product of Amperes, maximum possible exposure length, and frequency, aggregated along the feed length exposed to the train loadings. The second measure is the maximum Ampere-frequency product occurring on the catenary. Both measures were based on the substation power demand which is expected to occur once every two months, the same load used in the substation spacing analysis. The first measure is relevant for long parallel lines, while the second is relevant for short exposure lengths. The normalized values indicate that both the 25 kV, 60 Hz feed and the 25 kV, 25 Hz feed give noticeable reductions for the long-line case but that only the 25 kV, 25 Hz case is effective in the situation of a short exposure length. The corridor region is not included in the table because booster transformers were used in a manner giving the same Ampere-distance-frequency product for each case.

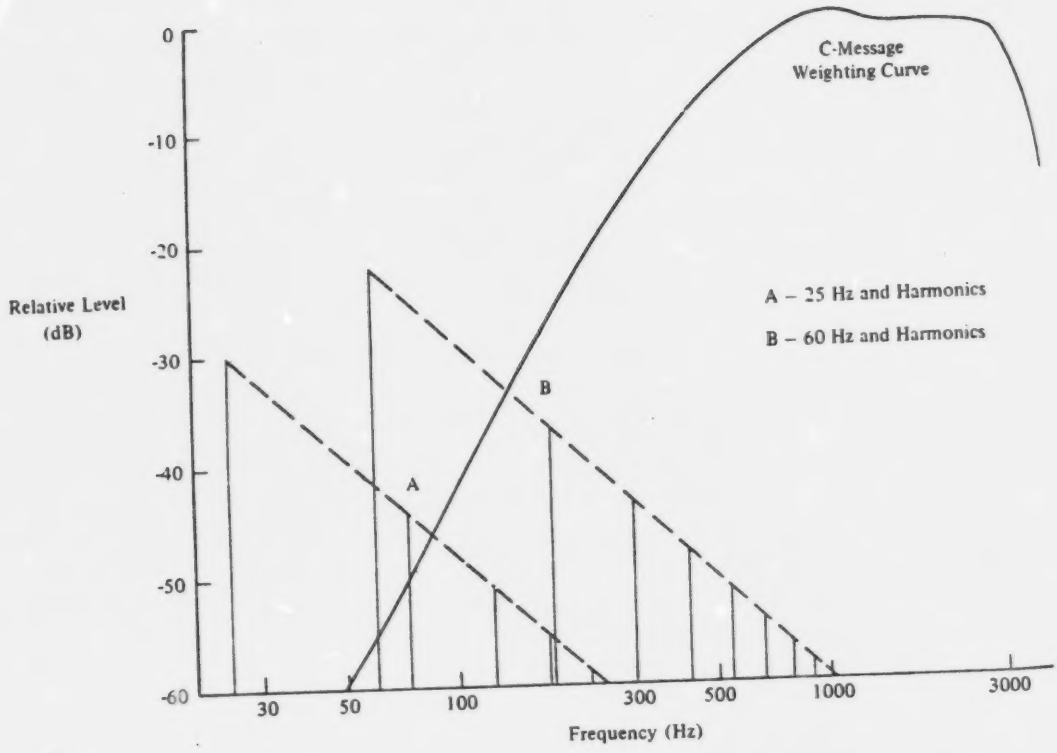
TABLE 3.17

RELATIVE INDUCTIVE INFLUENCE AT THE FUNDAMENTAL FREQUENCY

Region	Feed	Measure of Disturbing Influence		Normalized	
		kA.km.Hz	Maximum kA.Hz	A.Hz.km	kA.Hz
Mountain	50 kv,60 Hz	1,427	51.78	1.000	1.000
	25 kV,60 Hz	660	59.34	0.463	1.146
	25 kv,25 Hz	660	26.58	0.463	0.51
Prairie	50 kv,60 Hz	1,140	34.62	1.000	1.000
	25 kv,60 Hz	480	33.00	0.42	0.95
	25 kv,25 Hz	445	18.1	0.39	0.523

To consider the relative impact on noise voltages, one further step must be taken -- the harmonic content of the current must be considered. This is usually done by weighting the harmonic content such that those frequencies in the speech region (800-3,000 Hz) receive a higher weight. Bell Laboratories have estimated the increase in telephone noise content associated with a change in railway electrification from a 25 Hz feed to a 60 Hz feed.[13] The weighting curve used (the C-message weighting curve) and the harmonic content for 25 Hz and 60 Hz locomotives used in the evaluation are shown in Figure 3.11. The telephone influence factor (TIF) is the aggregate of the weighted harmonics and for the locomotives evaluated the values were 127 at 60 Hz and 31 at 25 Hz.

13 Carroll, R.L., Carter, A.H., "The Prediction of Inductive Interference in Telephone Circuits Resulting from Railroad Re-electrification," Symposium on Railroad Electromagnetic Compatibility, U.S. DOT Report No. FRA/ORD-80/46, May 1980.



Source: Carroll & Carter, op. cit.

Figure 3.11 Frequency spectrum of 25 Hz and 60 Hz electric locomotion

This term represents the fractional content of a weighted average frequency. Referring back to the induced voltage equation, $E = 2 \prod f M I \ell$, and the previous table which showed the f.I.ℓ product for the fundamental, one must multiply the TIF by I.ℓ to get the equivalent noise measure. Table 3.18 shows the noise measure which is equivalent to the fundamental measures of Table 3.18. For the 60 Hz case, the fundamental numbers are multiplied by the ratio 127/60, while for the 25 Hz case the ratio is 31/25. Thus, the normalized values are the same at 60 Hz and further reduced at 25 Hz.

TABLE 3.18

RELATIVE INDUCTIVE INFLUENCE AT NOISE FREQUENCIES

Region	Feed	Measure of Disturbing Influence		Normalized Values	
		kA.km.TIF	Maximum kA.TIF	kA.Hz.TIF	kA.TIF
Mountain	50 kV,60 Hz	3,020	109.6	1.000	1.000
	25 kV,60 Hz	1,397	125.6	0.463	1.146
	25 kV,25 Hz	818	33.0	0.271	0.301
Prairie	50 kV,60 Hz	2,413	73.28	1.000	1.000
	25 kV,60 Hz	1,016	69.85	0.42	0.95
	25 kV,25 Hz	552	22.44	0.229	0.306

4. FINANCIAL EVALUATION

In this section the cost estimates developed in the previous sections for the various alternatives will be compared on the basis of their net present value (NPV). Because of the high uncertainty of both the physical quantities and the unit costs associated with civil reconstruction for electrical clearance and measures to achieve electromagnetic compatibility (EMC), only the other costs will be aggregated. As these are the areas where a lower voltage and a lower frequency show savings, the high-voltage industrial frequency option will be the lowest-cost alternative for the subset of the relevant costs which are included in the aggregation. The savings shown by the high voltage, industrial frequency option will then be available in the future as more data on these two cost items are developed, thus permitting a comparison with the offsetting savings which may be obtained by the other alternatives in the areas of civil reconstruction and EMC.

While the alternatives will be compared on the basis of present value of the relevant costs, the present value will be separated into three time frames to provide more information on the cash flow consequences. Also, the reader may wish to place different weightings on the three time periods, even though they are of equal present value on the basis of the discount rate used. The three intervals are: the initial construction period, the first thirty years of operation, and the second thirty years of operation. As noted previously, the traffic is estimated to grow exponentially at about 1.7 per cent per annum over the first thirty years and to experience no changes for the second thirty years.

The relevant construction costs are assumed to occur in equal portions over the first two years and are estimated to experience a cost escalation rate equal to the general inflation rate. Engineering costs of 15 per cent of substation and utility feed costs are incurred in the first year and are considered to be an operating cost. For the catenary they are considered to be the same for all of the alternatives and are therefore excluded. The present value of the construction costs is therefore:

$$PV_c = 0.5(S+U+W) \times \left(1 + \frac{1+i}{1+k}\right) + (S+U) \times 0.15 \times (1-T)$$

where: S = substation cost

U = utility feed cost

W = overhead catenary cost

i = general inflation rate

k = weighted average cost of capital

T = corporate tax rate.

The relevant costs in the first thirty operating years are the electricity costs, substation maintenance costs and the tax savings from fixed facilities capital cost allowance. The present value of the costs and savings is:

$$PV = \sum_{n=3}^{32} \left(E \left(\frac{(1+i)(1+g_e)}{1+k}\right)^n + D \left(\frac{(1+i)(1+g_d)}{(1+k)}\right)^n + M \left(\frac{1+i}{1+k}\right)\right)^n \times (1-T)$$

$$- 0.5\,(S+U+W) \times \frac{TxC}{1-C} \left(\sum_{n=2}^{32} \left(\frac{1-C}{1+k}\right)^n + \sum_{n=3}^{32} \left(\frac{1-C}{1+k}\right)^n \right)$$

where: E = energy losses cost in year one

g_e = energy losses cost real growth rate for the first thirty years

D = utility demand charge in year one

g_d = demand charge real growth rate for the second thirty years

C = capital cost allowance rate.

At the beginning of the second thirty-year interval, the fixed facilities are estimated to require an investment of 40 per cent of the

original cost in 1981 dollars. Traffic volumes are assumed to remain constant in this period so the present value is:

$$PV = 0.4(S+U) \times \left(\frac{1+i}{1+k}\right)^{33} \times (1 + 0.15 \times (1-T)) + .4W \left(\frac{1+i}{1+k}\right)^{33}$$

$$+ (1-T) \times (E(1+g_e)^{32} + D(1+g_d)^{32} + M) \times \sum_{n=33}^{62} \left(\frac{1+i}{1+k}\right)^{n}$$

$$- .4\,(S+U+W) \times \frac{TC}{1-C} \times \sum_{n=33}^{62} \left(\frac{1-C}{1+k}\right)^{n}$$

The values of the cost items in the above formulae have been estimated and discussed in the previous section. The values of the financial parameters used in the above formulae are summarized in Table 4.1. It should be noted that the real growth exhibited by the energy and demand costs (g_e and g_d) are only tied to the traffic growth. No real price

TABLE 4.1

FINANCIAL PARAMETERS

Item	Description	Value Used
i	general inflation rate	0.1
g_e	energy cost escalation rate for the first thirty years	0.017
g_d	demand charge escalation rate for the first thirty years	varies with each case
k	weighted average cost capital	0.135
T	corporate tax rate	0.5
C	capital cost allowance rate for all relevant fixed facilities	0.06

escalation is included. The weighted average cost of capital (k) is based on a 40/60 debt/equity ratio with the before-tax cost of debt at 16 per cent and the return on equity at 17 per cent.

The NPV of the various alternatives are shown for the Mountain Region in Table 4.2. Each of the cost items developed in Section 3 are shown in the table for the four alternatives. All costs are expressed in terms of their equivalent present value on a 'per-route-km' basis. Thus, any cost item may be compared or aggregated with any other cost item. As noted previously, the subset of costs considered favour the 50 kV, 60 Hz alternative. Thus, the last column in the table, which aggregates the costs for each alternative, represents the costs which must be saved by the other alternatives in clearance and EMC costs (on a present value per route-km basis) to make them competitive with 50 kV, 60 Hz.

Comparing 25 kV, 60 Hz with 50 kV, 60 Hz, the initial construction cost premium is $60,900 per route-km. This results from a large premium for substation and utility feed costs, partially offset by the saving in catenary costs. The NPV of the first thirty years of operation has a cost premium of $139,000 per km. This includes the three operating cost items as well as the depreciation tax savings on the fixed installations. For the second thirty years the cost premium is $64,600 per km. The total premium is $264,500 per km. This amount would have to be saved in clearance and EMC costs to make 25 kV, 60 Hz a superior choice.

Comparing the individual cost items, the utility demand charges are the largest contributing factor, accounting for about two-thirds of the total net difference. However, it is possible that lower demand rates may be obtained in negotiations with the utilities or that peak demand reduction measures may be employed by the railways. These measures would lower the costs for alternatives but would also reduce the spread between them. Cutting the demand costs in half may be feasible and would reduce the 50 kV advantage to $174,300 per km. It should be noted, however, that the demand charges have been assumed to have no price escalation beyond the inflation rate and that the traffic growth rates are conservative. Thus it is also possible that a larger saving

TABLE 4.2

COST COMPARISON
Case: Corridor Region, 40 MVA Acceptable Imbalance

Alternative	Substation Spacing (km)	Time Period (years)	P.V. Cost (K$/route-km)						Required Saving Over 50 kV
			Substation and Utility Feed*	Catenary	Utility Demand	Energy Losses	Sub-station Maintenance	Total	
50 kV 60 Hz	78	1-2	70.0	158.7	-	-	-	228.7	-
		3-32	(10.2)	(23.3)	236.3	7.2	3.2	213.2	-
		33-62	8.0	19.2	109.0	3.5	1.3	141.0	-
		Total	67.8	154.6	345.3	10.7	4.5	582.9	-
25 kV 60 Hz	26	1-2	142.0	147.6	-	-	-	289.6	60.9
		3-32	(20.6)	(21.7)	366.7	18.0	9.8	352.2	139.0
		33-62	16.1	18.0	159.0	8.7	3.8	205.6	64.6
		Total	137.5	143.9	525.7	26.7	13.6	847.4	264.5
25 kV 25 Hz	68	1-2	252.0	156.9	-	-	-	408.9	180.2
		3-32	(37.0)	(22.9)	285.4	32.9	35.6	294.0	80.8
		33-62	28.7	19.2	133.5	15.9	14.0	213.3	70.3
		Total	243.7	153.2	418.9	48.8	49.6	914.2	331.2
12.5 kV d.c.	36 (23.8)	1-2	164.0	153.1	-	-	-	317.1	88.4
		3-32	(23.8)	(22.3)	340.2	39.3	15.2	348.6	135.4
		33-62	18.7	18.6	150.3	19.0	6.0	212.6	71.6
		Total	158.9	149.4	490.5	58.3	21.2	878.3	295.4

* includes engineering costs

would result. The sensitivity of the results to this and other factors is addressed in the next section.

One could achieve the same utility feed costs and demand charges for 25 kV as for 50 kV by feeding the 25 kV substations in sets of three, with subtransmission lines from the centre of the two adjacent substations. Because these two cost items were so significant, this alternative was briefly evaluated.

A recent feasibility study performed for Conrail by Gibbs and Hill estimated the incremental cost of a single-phase, 230 kV transmission line above the railway catenary to be $375,000 per mile ($232,500 per km).[1] On this basis there is no significant advantage. However, the estimated cost does seem to be quite high.

In Section 3.5 it was shown that the CN mountain region had an average of three bridges or snow sheds per 100 km and 486 m of tunnel per 100 km. Concerning EMC, it was shown in Section 3.6 that the 50 kV alternative would have about twice the disturbing influence of a 25 kV, 60 Hz system for long exposure of parallel conductors. Would the savings realized with 25 kV, 60 Hz for these two cost categories amount to the $264,500 per km necessary to make it competitive with 50 kV, 60 Hz?

In the mountains it is likely that most of the savings from 25 kV would have to come from reduced clearance costs as there are few communications cables near the railway right-of-way and those on the right-of-way would have to be modified regardless of the alternative chosen.

To make a rough estimate of the necessary savings, assume 90 per cent of the necessary savings must come from civil reconstruction and that the cost of raising one bridge is equivalent to raising 15 m of tunnel for a 50 kV catenary. The PV of the cost of this work must recognize

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1 Gibbs & Hill, Inc., Electrification Feasibility Study, November 1979.

future depreciation allowance, which may be expressed as:2

$$\frac{TC}{k+C}$$

For the financial parameters used previously, the effect is to reduce the first cost to 84.6 per cent. The unit cost of clearance-related construction must then be greater than:

$$\left(\frac{0.9 \times 264{,}500}{0.846}\right) \qquad \left(\frac{486 + 3.0 \times 15}{100}\right)$$

That is, 25 kV, 60 Hz would be superior to 50 kV, 60 Hz under the estimated mountain conditions if the incremental cost of tunnel excavation under 50 kV is greater than $53,000 per metre and the cost of bridge modifications greater than $795,000 per bridge. If a 6.4 m (21 ft) load height is specified, then the slope of the line in region C of the cost curve discussed in Section 3.5 must be greater than $1,000 per cm of vertical clearance/metre of tunnel and greater than $15,000 per cm of clearance for each bridge. If 5.94 m (19.5 ft) load height is required, then much of the clearance problems fall into regions A and B for the 25 kV case, in which case the savings of the required magnitude are more likely to be feasible. Here, one requires that the 'average' cost per cm be greater than the above values rather than the 'marginal' cost of region C. Current railway estimates of new tunnelling costs vary from $9,000 to $30,000 per metre, depending on rock conditions and tunnel length.[3] These costs are for a complete 7 m high tunnel, whereas the 50 kV alternative requires, at most, 50 cm more clearance than does 25 kV. Similarly, the cost of a completely new highway or railway overpass has been estimated by CIGGT to be lower than the

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2 "Discounted Cash Flow Procedures Suitable for Mine Feasibility Analysis and Stockpiling Decisions," R.W. Lake and E.B. Wilson, CIM Annual Meeting, 1977.

3 CP News, 11 September 1981.

required cost of modifications shown above.[4] On the basis of these estimates and the assumed conditions, 50 kV would be superior, even with one-half the demand charge and a 5.94 m load height.

The clearance data are based on existing single-track conditions, while our analysis has been based on double track operations. The incremental cost of attaining higher clearances at the initial double-track construction phase are considered to be much less than the incremental cost of reconstruction on an operating line. However, this point should be considered as more detailed data become available. Consideration of single-track instead of double-track operation for the same traffic densities would further the advantage of the higher voltage since the catenary savings per route-km of the lower voltage would be less and the current requirement which was met by parallel catenaries under double-track operation would require extra conductors at the lower voltages.

The other two alternatives shown in Table 4.2 (25 kV, 25 Hz and 12.5 kV, dc) both have a higher NPV than the 25 kV, 60 Hz alternative and much of the difference is in the initial construction costs. For the 25 kV, 25 Hz case, the clearance costs are the same as for 25 kV, 60 Hz, so the total cost difference of about $65,000 per km would have to be recovered through EMC savings. As noted earlier, it is unlikely that differential EMC costs of this magnitude would occur in the Mountain region. The 12.5 kV, dc case would demonstrate savings in both EMC and clearance and may be competitive with 25 kV, 60 Hz. However, it is not yet technically feasible. If feasible, it is unlikely to realize sufficient savings to be competitive with 50 kV, 60 Hz. If it were possible to distribute and utilize dc at a voltage higher than 12.5 kV, then the dc option may be competitive with 50 kV, 60 Hz, but such a system is unlikely to be feasible in this decade.

The NPV's of the alternatives are compared for the estimated conditions in the prairie and corridor regions in Tables 4.3 and 4.4 respectively.

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4 Lake, R.W., et al., Alternatives to Air: A Feasible Concept for the Toronto-Ottawa-Montreal Corridor, CIGGT Report No. 80-4, July 1980. The average cost of non-urban road over rail crossings was estimated at $400,000 in 1978 dollars.

TABLE 4.3

COST COMPARISON
Case: Prairie Region, 20 MVA Acceptable Imbalance

Alternative	Substation Spacing (km)	Time Period (years)	P.V. Cost (K$/route-km)						Required Saving Over 50 kV
			Substation and Utility Feed*	Catenary	Utility Demand	Energy Losses	Sub-station Maintenance	Total	
50 kV 60 Hz	87	1-2	48.2	158.7	-	--	-	206.9	-
		3-32	(6.9)	(23.3)	150.6	4.6	3.2	128.2	-
		33-62	5.5	19.2	66.2	2.3	1.3	94.5	-
		Total	46.8	154.6	216.8	6.9	4.5	429.6	-
25 kV 60 Hz	32	1-2	85.1	147.6	-	--	-	232.7	25.8
		3-32	(12.2)	(21.7)	225.2	11.4	7.9	210.6	82.4
		33-62	9.7	18.0	110.3	5.7	3.1	136.8	42.3
		Total	82.6	143.9	335.5	17.1	11.0	580.1	150.5
25 kV 25 Hz	81	1-2	174.7	156.9	-	-	--	331.6	124.7
		3-32	(25.0)	(22.9)	173.6	20.5	25.7	171.9	43.7
		33-62	19.9	19.2	75.8	10.2	10.0	135.1	40.6
		Total	169.6	153.2	249.4	30.7	35.7	638.6	209.0
12.5 kV d.c.	48	1-2	103.7	153.1	-	-	-	256.8	49.9
		3-32	(14.8)	(22.3)	210.0	27.3	8.2	208.4	80.2
		33-62	11.8	18.6	100.8	13.6	3.2	148.0	53.5
		Total	100.7	149.4	310.8	40.9	11.4	613.2	183.6

* includes engineering costs

TABLE 4.4

COST COMPARISON
Case: Mountain Region, 20 MVA Acceptable Imbalance

Alternative	Substation Spacing (km)	Time Period (years)	P.V. Cost (K$/route-km)						Required Saving Over 50 kV
			Substation and Utility Feed*	Catenary	Utility Demand	Energy Losses	Sub-station Maintenance	Total	
50 kV 60 Hz	74	1-2	48.5	168.8	-	-	-	217.3	-
		3-32	(6.9)	(25.0)	172.7	4.8	3.4	149.0	-
		33-62	5.5	20.4	77.5	2.4	1.3	107.1	-
		Total	47.1	164.2	250.2	7.2	4.7	473.4	-
25 kV 60 Hz	26	1-2	117.5	168.6	-	-	-	286.1	68.8
		3-32	(16.8)	(24.9)	233.7	12.0	9.8	213.8	64.8
		33-62	13.4	20.4	106.4	5.9	3.8	149.9	42.8
		Total	114.1	164.1	340.1	17.9	13.6	649.8	176.4
25 kV 25 Hz	65	1-2	175.1	166.6	-	-	-	341.7	124.4
		3-32	(25.0)	(24.6)	212.9	21.6	24.1	209.0	60.0
		33-62	19.9	20.2	97.5	10.7	9.4	157.7	50.6
		Total	170.0	162.2	310.4	32.3	33.5	708.1	235.0
12.5 kV d.c.	45	1-2	106.8	153.0	-	-	-	259.8	42.5
		3-32	(15.3)	(22.3)	222.0	28.8	10.2	223.4	74.4
		33-62	12.1	18.6	102.4	14.3	4.0	151.4	44.3
		Total	103.7	149.4	324.4	43.1	14.2	634.6	161.2

* includes engineering costs

Although the difference in NPV between 50 kV and 25 kV, 60 Hz is lowest in the Prairies, the incidence of overhead clearance problems is lower. For the CN clearance data for Winnipeg to Edmonton and using the same analysis as above, the incremental cost per bridge would have to be $12.3 million, more than ten times the requirement for the mountains.

In the corridor, the dc option shows a relative improvement because all of the ac options have the incremental catenary costs and shorter substation spacing resulting from the use of booster transformers for EMC. The booster transformers were applied to the different ac options so that each would have the same amp-frequency-km rating. Thus, the dc option is the only one which would show a significant reduction in EMC costs. As a rough estimate of corridor conditions, assume one-half of the cost savings must come from clearance and one-half from EMC. As there are 12.8 bridges per 100 route-km in this region, the associated minimum unit costs would then be:

$$\left(\frac{0.5 \times 161.2}{0.846}\right) \quad \left(\frac{12.8}{100}\right) = \$743{,}000/\text{bridge}$$

and

$$\frac{0.5 \times 161.2}{0.846} = \$95{,}000/\text{route-km for EMC}$$

These values are in the range of feasibility for the types of highway bridges and communications networks involved in the corridor, but it only puts the dc option in the range of indifference in comparison to 50 kV. In consideration of the other regions of the total rail system, the dc option would only be chosen in the corridor if a higher voltage dc option were feasible for application in the other regions. The other two ac alternatives offer reduced clearance and EMC savings and are likely to be competitive with 50 kV for the conditions estimated here. For example, 25 kV, 60 Hz might have to realize 90 per cent of the savings from clearance costs since the use of booster transformers almost equalizes the EMC conditions. The unit bridge cost differential would then have to be $1.47 million for 25 kV to be competitive for the estimated corridor conditions.

For the base condition estimates and assumptions made in the above analysis, it appears that 50 kV is the superior option for the Prairies and, with existing technical limitations for dc voltages higher than 6 kV, is likely to be superior or at least competitive with the other options in the corridor and mountain regions. However, there is a certain amount of uncertainty regarding the values used and some of the more uncertain parameters will be evaluated for sensitivity in the next section.

4.1 SENSITIVITY ANALYSIS

4.1.1 Sensitivity to Financial Parameters

As was noted previously, the major cost differential for 25 kV, 60 Hz and 50 kV, 60 Hz is the demand charge predicted to occur over the first sixty operating years. This cost item is easily modified. Train speeds and/or schedules may be altered temporarily so as to reduce both the localized congestion, and the use of full power, which produces high demand charges. The railways may be able to negotiate lower demand charges, or they may be able to implement an aggregated system-wide demand meter rather than individual substation metering.[5] This would result in basically the same demand charges for 50 kV and 25 kV, regardless of the rate charged. The consequences of a 50 per cent reduction and a total elimination of the demand charge on the minimum unit clearance costs required to make 25 kV, 60 Hz competitive with 50 kV are illustrated in Table 4.5. Total elimination of the demand charge differential would possibly put 25 kV, 60 HZ in a competitive position with 50 kV in the mountain and corridor regions, but it would appear to be uncompetitive for all other combinations in the table.

Since the largest component of the 50 kV cost savings occurs in the operating years, its advantage will be diminished by those parameters which lower the NPV. A lower traffic growth rate, or a higher required return on equity, will have this effect. The estimated traffic growth rate of 1.7 per cent per annum over the first thirty years and zero over the second thirty years is considered conservative, but Table 4.6

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5 However, the pipeline companies have pressed to have system-wide metering of their pumping stations but have not succeeded.

TABLE 4.5

SENSITIVITY TO DEMAND CHANGE

25 kV-50 kV Demand Charge Differential	Mountain Region		Prairie Region (M$/bridge)	Corridor Region (M$/bridge)
	Tunnels (K$/m)	Bridges (M$/unit)		
Base Case	53.0	0.795	12.3	1.47
50% Reduction	35.0	0.525	7.8	1.09
100% Reduction	17.0	0.256	3.4	0.69

TABLE 4.6

SENSITIVITY TO TRAFFIC GROWTH

Growth Rate	Mountain Region		Prairie Region (M$/bridge)	Corridor Region (M$/bridge)
	Tunnels (K$/m)	Bridges (M$/unit)		
Base Case	53.0	0.795	12.3	1.47
50% Reduction	46.9	0.703	10.8	1.34

TABLE 4.7

SENSITIVITY TO RETURN ON EQUITY

Return on Equity	Mountain Region		Prairie Region (M$/bridge)	Corridor Region (M$/bridge)
	Tunnels (K$/m)	Bridges (M$/unit)		
Base Case (17%)	53.0	0.795	12.3	1.47
50% Increase (25%)	29.3	0.446	6.3	0.90

illustrates the effect of halving the growth rate to 0.85 per cent per annum for the first thirty years. It has very little influence. A significant increase in the required return of equity has a more dramatic effect, but is still less than those produced by the demand charge reductions. The consequences of a 25 per cent return rather than a 17 per cent base case value are illustrated in Table 4.7.

4.1.2 Sensitivity to Shorter, More Frequent Trains

The effects of operating shorter and more frequent trains have also been evaluated. The mountain region conditions were used, but the bulk trains were reduced in length and power by 33 per cent and the general freight trains were reduced in length and power by 50 per cent. This resulted in a reduction of the substation power demand such that the substation spacing could be increased by 12.5 per cent for the 50 kV case and by 25 per cent for the 25 kV, 60 Hz case. Also, the metered demand readings were estimated to be unchanged, even with the inreased spacing. As a result, all but the energy and catenary costs were decreased on a unit distance basis by 12.5 per cent and 25 per cent for 50 kV and 25 kV respectively. In dollar terms this produced a net reduction of $52,200 per route-km for 50 kV and $169,200 per route-km for 25 kV. This would improve the position of 25 kV over the base case conditions to the point where the minimum unit clearance cost would be $29,600 per metre of tunnel and $443,000 per bridge. Without the simultaneous occurrence of some of the changes of base conditions evaluated above, this still leaves 25 kV, 60 Hz in a relatively poor position in relation to 50 kV.

In considering the likelihood of short train operation, one must consider the incremental crew costs which accompany the above saving. Also, infrastructure capacity costs would be increased at some point. The year-thirty base-case operations involved an estimated 52 trains per day in peak periods, while the short-train strategy would involved 68 trains per day.

4.1.3 Sensitivity to the Utility Imbalance Limit

The effects of the utility imbalance limit are included in the base-case analyses to a certain extent. The corridor region has a higher value and permits lower unit substation costs for the three alter-

natives which are most influenced by it -- 50 kV and 25 kV at both 60 Hz and 25 Hz. The effect on the ranking of the alternatives is not significant, however. A reduction of the imbalance limit from 20 MVA to 10 MVA is also evaluated in the mountain and prairie regions. The effect on substation costs was discussed previously in Section 3.2. The net effect on the required savings of the 50 kV case arises from the substation and substation maintenance costs, and amounts to the savings shown in Table 4.8, none of which are significant in terms of the ranking of alternatives.

TABLE 4.8

EFFECT OF CHANGING WITH LOAD IMBALANCE LIMIT FROM 20 MVA TO 10 MVA

	Reduction (Increase) in Required Cost Savings over 50 KV (%)	
Alternative	Mountain	Prairie
25 kV, 60 Hz	(0.1)	(1.55)
25 kV, 25 Hz	3.4	2.4
12.5 kV, dc	3.4	2.4

4.2 MIXED VOLTAGE OPERATION

The foregoing analysis has shown that 50 kV is likely to be competitive for each of the regional average characteristics and desirable for 'Prairie' conditions. However, the average density of clearance obstructions is much lower at the region level than exists in certain subsections of the regions. For example, CN's Yale and Ashcroft subdivisions have segments with ten times the regional average tunnel density. Also, the bridge frequency in the Toronto area is three times the average for Toronto-Montreal. If these short segments were operated in isolation from the rest of the rail system, a lower voltage would certainly be superior, but they are part of an integrated rail system. The question arises, "should a lower voltage be used at short

segments of a rail system which is electrified at a higher voltage elsewhere?"

As far as the locomotive is concerned, there is no problem. The British Railways operate through the London tunnel at 6.25 kV, while the rest of the system is at 25 kV. A dual voltage locomotive, capable of operating on any multiple of 50 kV, in addition to 50 kV, is possible. The transformer aboard the locomotive will require the same multiple of windings and switch gear which will either connect the windings in series (50 kV) or in parallel (the lower voltage). The pantograph and high voltage bus bar must be insulated for 50 kV and capable of carrying the current loads of the lower voltage. Manufacturers have quoted an additional cost of one to two per cent for the dual voltage locomotive.

Consider, for example, electrification of some segments at 25 kV, and some at 50 kV. A dual-voltage locomotive, running from 50 to 25 kV catenary, would see a sudden loss of power as the pantograph passed over the catenary insulator, and then a re-energization at a lower voltage (below the normal operating range). The problem is very similar to that of a phase break, discussed in Section 3.1.5. It would be necessary to power the locomotive down prior to the catenary insulator, and to operate the locomotive voltage changing switchgear prior to powering up after the insulator. For a single locomotive, proper selection of the insulator location should permit the changeover without severe operational problems. The process might be automatic.

However, multiple locomotives, and particularly robot power, would substantially increase the operational complexity, and the effects of train action must be considered.

Whether this mode of operation is desirable economically depends on both the degree of integration with the rest of the rail system and the sequential timing of the conversion to electrified operations. The financial evaluation must weigh the incremental cost for locomotives operating over that segment and the added risk of malfunction in future operations against the clearance cost savings. The degree of integration determines how many locomotives must have a dual-voltage capability and the sequential timing of conversion to electric operations

determines to what extent the future clearance savings must be discounted to determine their present value.

To look at dual voltage operation in an optimistic light, assume that the Yale and Ashcroft subdivisions come on line first, with the rest of the Mountain region completed over a six-year interval. Also assume the Mountain region locomotives can be isolated from the rest of the system (i.e. all trains change power at Edmonton). Finally, assume there will be no future mishaps or maintenance charges associated with the dual-voltage operation. An estimated 28 locomotives would come on stream in each of the six years. An additional 1.7 per cent (three locomotives) per year will be added each subsequent year for traffic growth and the economic life is estimated to be thirty years. Using a 1.5 per cent cost increment ($30,000) for dual-voltage capability, the NPV of incremental locomotive costs is:

$$30{,}000 \times 38 \times \left(1 + \sum_{n=2}^{6} \left(\frac{1.1}{1.135}\right)^n + \sum_{n=31}^{36} \left(\frac{1.1}{1.135}\right)^n\right)$$

$$+ 30{,}000 \times 3 \times \sum_{n=7}^{66} \left(\frac{1.1}{1.175}\right)^n = \$7.3 \text{ million}$$

The clearance costs which must be saved in the two 25 kV substation sections is thus $7.3 million plus the lost savings of 50 kV operation, shown previously to be $264,000 per km. The necessary unit length cost saving for these two 26-km substation intervals is thus:

$$7{,}300/52 + 264 = 278 \text{ K\$ per km}$$

With ten times the tunnel density and only a modest increase in the required savings, the necessary unit tunnel savings are reduced from $53,000 per tunnel-meter to $5,600 per tunnel-meter. This is in the lowest part of the average estimated cost range discussed earlier and may also be near the unknown marginal cost per cm of additional clearance. Even if it was desirable to have all locomotives on the total system interchangeable, which might quadruple the NPV of incremental locomotive costs and the low voltage subdivisions were electrified

twenty years after conversion started (reducing the NPV of the clearance savings by a factor of 1.87), the necessary unit clearance savings would still be in the average cost range.

The situation in the Toronto area is different because the GO Transit commuter service which is considering electrifying is an isolated service. The CN's major freight movements bypass that area so there is little concern of integrating this area with future mainline freight electrification. However, the GO service may eventually want to expand to both the east and west onto track where CN does have major freight movements. Also, if VIA's intercity passenger service is electrified, it would undoubtedly share trackage with GO. The relative timing of these events then becomes the determining factor. It is possible that an electrified GO service would see most of its economic life before freight or intercity passenger electrification occurs in the corridor region. However, it may be desirable to install higher voltage insulators and mast heights on a lower voltage system to ease the conversion to a higher voltage if one of the other parties wishes to electrify at a higher voltage in the future for its through operations.

5. CONCLUSIONS AND RECOMMENDATIONS

The lack of precision in the unit costs and some of the physical quantities do not permit a high level of confidence in the actual numbers derived in the analysis. However, the significant differences between the 50 kV option and the others and the results of the sensitivity analysis leads one to conclude that a high voltage such as 50 kV should be applied in major parts of the Canadian railway system. The analysis would also suggest that a lower frequency ac option is not an economical choice due to the high cost of the necessary conversion equipment. The analysis also shows that a dc option is not going to be competitive at a voltage as low as 12.5 kV.

The use of a lower voltage such as 25 kV at 60 Hz is unlikely to be economically superior for major operating regions, but its use on a substation length segment (about 26 km) within a 50 kV network may be desirable. The final decision on voltage change for segments this short must consider the operating implications, the degree of integration with the remainder of the system and the planned electrification sequence.

On the basis of our analysis, it is recommended that technical research into overcoming the constraints of dc electrification only be undertaken if voltages of the order of 20 kV or higher are considered to be a feasible outcome of the research. Pursuing advances to 6 kV or 12 kV is unlikely to be of value to the Canadian situation.

It is recommended that, if electrification of any part of the Canadian rail network proceeds before relevant new technical developments occur, it be compatible with 50 kV, 60 Hz. This recommendation is based on the present analysis as well as the fact that 50 kV is an internationally accepted voltage. Given the considerable savings demonstrated by 50 kV, it is recommended that the technical limitations to railway voltages in excess of 50 kV be monitored for further development. If the use of a dual-voltage locomotive with small segments of low voltage is operationally acceptable to the railways, then a combination such as 60 kV/20 kV or 66 kV/22 kV may be superior. The major limitation to higher voltages is the higher voltage equipment (particularly the breaker) which must be installed on the locomotives.

Lesser problems are associated with the longer phase breaks in the catenary and detection of distant faults as opposed to normal operating loads as the feed distances become longer.

Finally, it is recommended that attempts be made to improve the data upon which the decisions associated with railway electrification are based. This applies to the physical quantities and characteristics of clearance obstructions and wayside conductors, and also to the development of reliable cost information.

APPENDIX A

EXPECTED NUMBER OF TRAINS ON A DOUBLE TRACK SEGMENT

Considering a substation spacing 'D', the probability of a train of type j being in that substation interval is:

$$P_{(j)} = \frac{D}{V_j} N_j$$

where: P_j = probability that a train of type j is in section D

V_j = average speed of j over section D

N_j = number of train type j dispatched per unit time

To ensure that the associated load will be seen for a reasonable time interval, the interval D, or time D/Vj, may be reduced by a suitable interval. For convenience D/Vj will be reduced by the demand metering interval MI (usually 15 minutes).

For n independent train types, the combined probability of seeing any m of them within interval D at one time is:

$$CP_m = \sum_{j_1}^{n+1-m} \sum_{j_2=j_1+1}^{n+2-m} \cdots \sum_{j_m=j_1+m-1}^{n} P_{j_1} P_{j_2} \cdots P_{j_m} * \prod_{k \neq j_i,\ i=1,m} (1-P_k)$$

and the expected load associated with those m trains is:

$$EL_m = \sum_{j_1}^{n+1-m} \sum_{j_2=j_1+1}^{n+2-m} \cdots \sum_{j_m=j_1+m-1}^{n} P_{j_1} P_{j_2} \cdots \frac{P_{j_m} * \prod_{k \neq j_i,\ i=1,m} (1-P_k) \ (L_{j_1} + L_{j_2} + L_{j_m})}{CP_m}$$

APPENDIX B

VOLTAGE IMBALANCE MITIGATION TECHNIQUES AT RAILWAY SUBSTATIONS

Voltage imbalances occur when unbalanced power is drawn from a three-phase power distribution system. This imbalance occurs because there is a voltage drop in each phase which is equal to the phase current times the distribution system impedance. Loads of a different magnitude draw different currents, resulting in different voltage drops in each of the phases. This effect is illustrated in Figure B.1. For a single-phase load, the imbalance created in the three-phase system is directly proportional to the magnitude of the load and to the system impedance of the high voltage distribution network. The inverse of the three-phase short-circuit input capability of the distribution system at the connection point is a surrogate for distribution impedance and the relative voltage imbalance may be expressed as the ratio of the single-phase load in MVA to the three-phase fault input in MVA.

To describe unbalanced voltage mathematically, one may use three sets of symmetrical components -- a positive sequence, a negative sequence and zero sequence.[1] The vectors are illustrated in Figure B.2. Any voltage condition can be derived by adding the three sets of components. It is the negative sequence components which present a problem. The positive phase sequence of a normal three-phase distribution system creates the rotating magnetic field which causes three-phase motors to turn. A negative-phase sequence superimposed on the positive-phase sequence produces an opposing torque. As a consequence, motor efficiency drops and heating increases. Woll has estimated a 35 per cent increase in losses and a 50 per cent increase in heating associated with a five per cent voltage imbalance.[2]

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1 The relevant theory may be reviewed in most text books on power systems analysis. See for example, W.D. Stevenson, Elements of Power Systems Analysis, McGraw-Hill.

2 Woll, R.F., "Effect of Unbalanced Voltage on the Operation of Polyphase Induction Motors," IEEE Transactions on Industry Applications, January/February 1975, Vol. IA-11, No.1.

Figure B.1 Balanced and unbalanced three-phase voltage supply

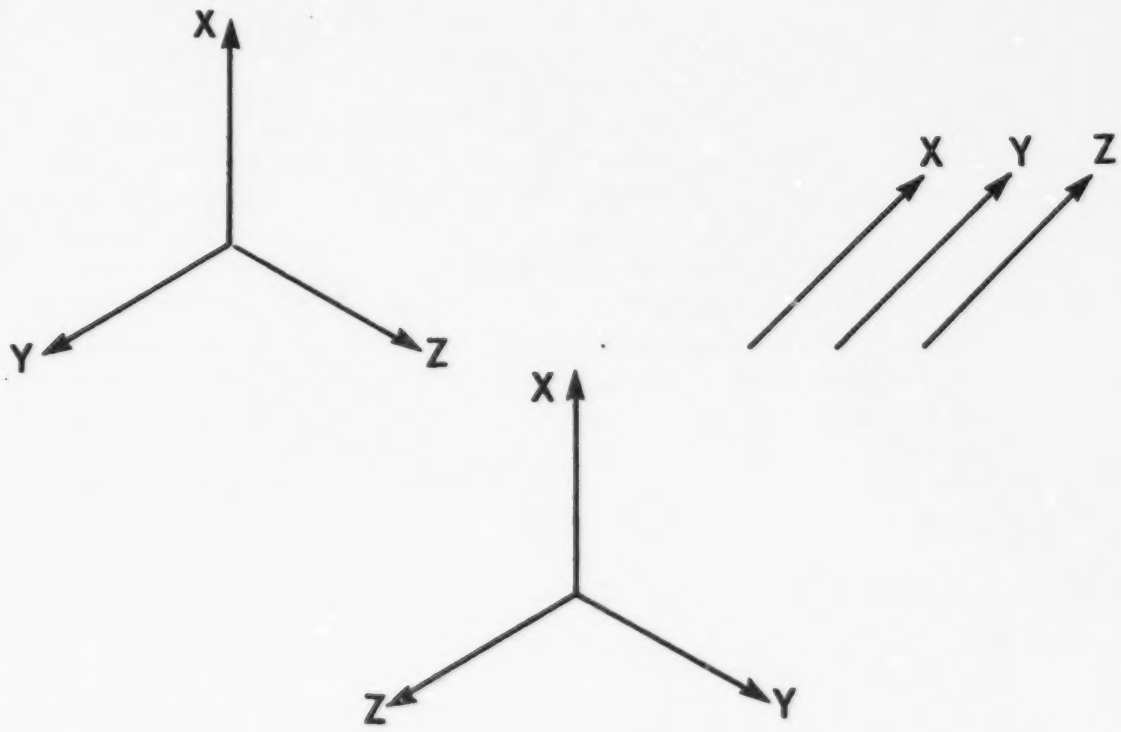

Figure B.2 Symmetrical components

The voltage imbalance is defined as the ratio of the magnitudes of the negative-phase sequence voltage (Vnps) to the positive-phase sequence voltage (Vpps) and Vnps is proportional to the negative-phase sequence currents (Inps) which are associated with the unbalanced load. For a three-phase load with phase currents Ix, Iy, Iz, the associated value of Ix_{nps} may be expressed as:

$$\dot{I}x_{nps} = \frac{1}{3}(\dot{I}x + a^2\dot{I}y + a\dot{I}z)$$

where 'a' is the vector $1\angle 120°$ (i.e. with a magnitude of one and a phase relationship of +120°) and a^2 is thus $1\angle 240°$.[3] Therefore, if one knows the value of the three-phase currents associated with a given load, the negative-sequence current can be calculated and the relative voltage imbalance predicted.

The four types of connections used to obtain a single-phase railway load in the present analysis are illustrated in Figure B.3. The voltage imbalance associated with each of these connections will be compared.

B.1 CENTRE FEED

The centre-feed connection will be taken as a reference. It has been noted that the voltage imbalance associated with such a direct single-phase tap is equal to the ratio of the load to the supply fault input, in this case:

$$V_{ub} = \frac{L_1 + L_2}{F}$$

where L_1 and L_2 are the railway loads on each side of the centre connection and F is the three-phase fault input capability at that point.

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3 The notation used is: $\dot{I}$ represents the vector with magnitude I and phase angle $\angle 0$.

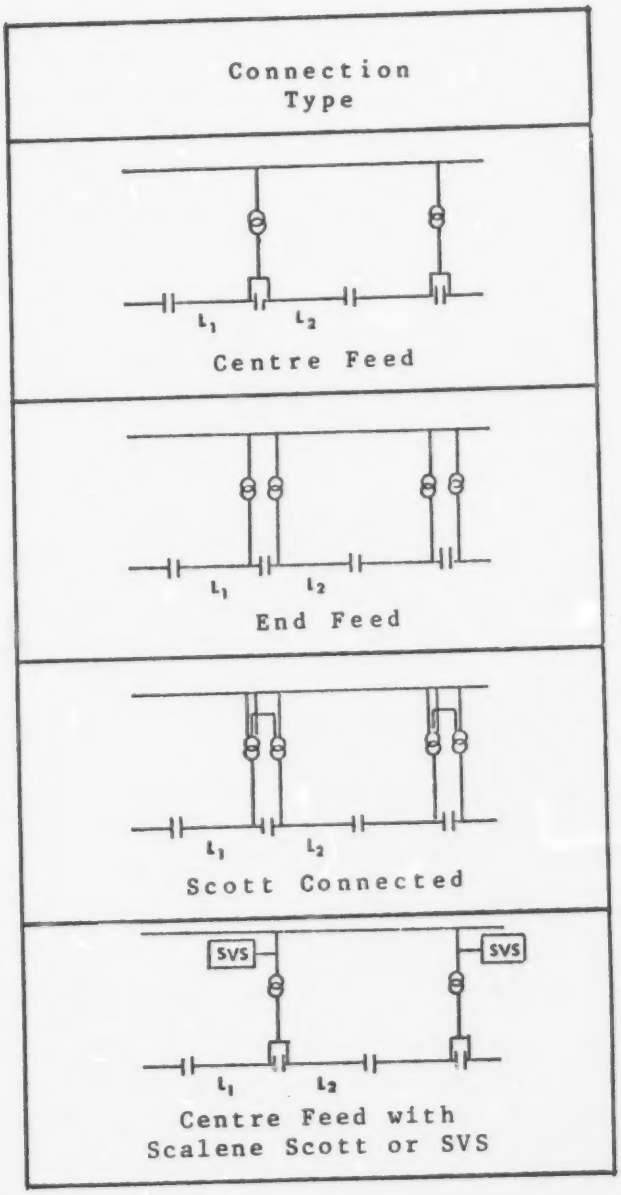

Figure B.3 Substation connections analyzed

For this connection, $Ix = I_1 + I_2$, $Iy = 0$ and $I_z = -(I_1+I_2)$. The negative-sequence current is thus:

$$Inps = \frac{1}{3}(I_1 + I_2 + a(-I_1-I_2)) = \frac{1}{\sqrt{3}}(I_1 + I_2)$$

B.2 END FEED

For the end-feed connection, $\dot{Ix} = I_1\angle 150°$, $\dot{Iz} = I_2\angle -150°$ and $\dot{Iy} = -I_1\angle 150 - I_2\angle -150°$. Thus, the negative-sequence current is:

$$Inps = \frac{1}{3}(I_1\angle 150 - a^2(I_1\angle 150 + I_2\angle -150) + a\, I_2\angle -150)$$

$$= \frac{I_2\angle -60}{\sqrt{3}} - \frac{I_1\angle 0}{\sqrt{3}}$$

and the voltage imbalance in relation to the centre-feed case is:

$$V'_{ub} = V_{ub}\left(\frac{I_2\angle -60 - I_1\angle 0}{(I_1 + I_2)\angle 0}\right)$$

In the case where $I_1 = I_2$, the imbalance is one-half that of the centre feed connection.

B.3 SCOTT CONNECTION

The Scott connection is a means of presenting a balanced three-phase connection for a balanced two-phase load. The connection used and its phasor diagram are illustrated in Figure B.4. With this connection:

$$\dot{Ix} = \frac{2}{\sqrt{3}}\dot{I}_1$$

$$\dot{Iy} = -\frac{1}{\sqrt{3}}\dot{I}_1 - \dot{I}_2$$

$$\dot{Iz} = -\frac{1}{\sqrt{3}}\dot{I}_1 + \dot{I}_2$$

The negative-sequence current is therefore:

$$Ins = \frac{1}{3}\left(\frac{2}{\sqrt{3}} I_1 \angle 0 - a^2\left(\frac{I_1\angle 0}{\sqrt{3}} - I_2\angle 90\right) + a\left(I_2\angle 90 - \frac{I_1\angle 0}{\sqrt{3}}\right)\right)$$

$$= \frac{I_1\angle 0 - I_2\angle 0}{\sqrt{3}}$$

In relation to the centre-feed case, the voltage imbalance is:

$$V''_{ub} = V_{ub}\left(\frac{I_1 - I_2}{I_1 + I_2}\right)$$

In this case, when $I_1 = I_2$, $V_{ub} = 0$.

The Scott connection does not permit a ground on the high-side connection, as can be seen in Figure B.4. In situations where the electrical utility requests a grounded Y connection, the Japanese National Railway system uses a Modified Woodbridge connection as illustrated in Figure B.5.[4] This connection is more expensive than the Scott, as it requires two three-phase transformers and one autotransformer and is not as effective as the Scott connection in mitigating voltage imbalance. We did not use this form of connection in the present analysis.

B.4 REACTIVE ELEMENT LOAD BALANCING

If the voltage imbalance cannot be reduced to an acceptable level by transformer connections, then load balancing by variable reactive elements might be employed in conjunction with a centre-feed transformer connection. ASEA has installed such a system at the South

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4 Akai, M., "Latest Developments in Electric Railway Substations," Toshiba Review, April 1972.

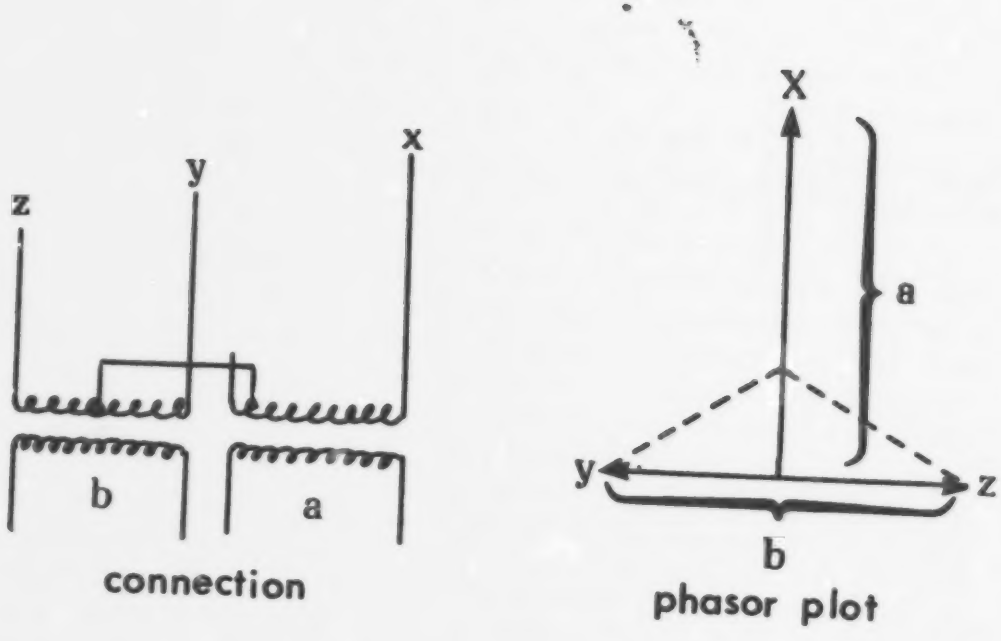

Figure B.4 The Scott-connected transformer

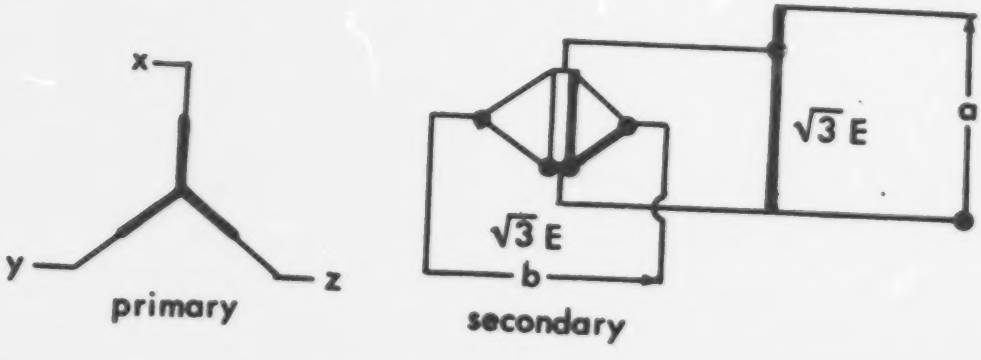

Figure B.5 The modified Woodbridge connection

African 50 kV railroad substation in Ferrum.[5] The system utilizes thyristor-controlled reactors to produce a continuously variable inductance, and breaker-switched capacitor banks to produce discretely variable capacitance. The details of how this system achieves a balanced load is described in an ASEA brochure which is copied here as Appendix C.

B.5 SCALENE SCOTT-CONNECTION WITH REACTIVE LOAD BALANCING

The JNR has selected this system over the centre-feed tap with reactive load balancing because it reduces the reactive power capacity requirement as well as the number of banks which must be controlled. The system is fully described and compared with alternatives by Arai.[6] In situations where the power factor of the load is relatively constant, a balanced three-phase load with a power factor greater than 90 per cent may be obtained by adding one bank of capacitors to the teaser secondary winding such that the reactive power of the capacitors is equal to the total apparent power of the load. A unity power factor may be obtained by placing an inductive load across the winding and reducing the capacitance in the teaser such that the sum of the reactive powers equals the apparent power of the load. Figure B.6 illustrates the connection used. For a known power factor, Θ, of the load, the teaser and main windings must be wound such that:

$$V_T = V_L \cos\left(\frac{\pi}{4} - \frac{\Theta}{2}\right)$$

$$V_M = V_L \sin\left(\frac{\pi}{4} - \frac{\Theta}{2}\right)$$

---

5 "The Static VAR System in Ferrum - A Proof of Flexibility," ASEA Pamphlet No. NR 500-001E, November 1980.

6 Arai, K., "Balancing Method for Three-Phase Power System Supplying Single-Phase Load by Means of Scalene Scott-Connected Transformer Assembly," Railway Technical Research Institute, Quarterly Report, Vol. 22, No. 1, 1981.

where V_T, V_M and V_L represent the teaser, main and load voltage respectively.

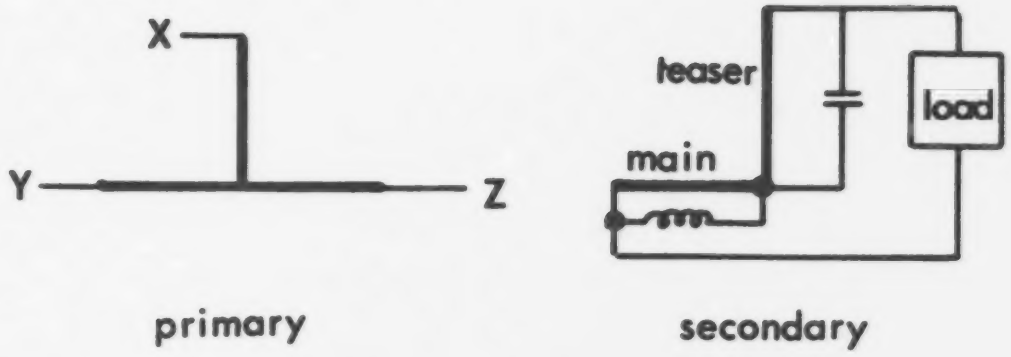

Figure B.6 Scalene Scott-connection

If the power factor of the load is not constant, then each secondary winding must have on-load tap changers with a sufficient range to permit the above voltage relationships to be maintained. The advantages of this method over the centre tap with reactive load balancing on the primary side thus depends on the nature of the load. If the load power factor is relatively constant and a 0.9 power factor is acceptable, about two-thirds of the reactive power is required and one rather than three control systems is used. If the load power factor varies and a unity power factor is desired on the primary side, the total reactive power does not change, but two controlled banks are necessary as well as on-load tap changers with control.

B.6 COMPARISON OF EFFECTIVENESS

The reactive load balancing system can balance any size of load within the discrete step size of the capacitor banks and is therefore the most effective of the four connections discussed. However, it is more expensive than simple transformer connections. The selection priority used in the analysis was centre feed, end feed, Scott connection, and finally, reactive load balancing. The relative effectiveness of the first three systems is illustrated in Figure B.7.

African 50 kV railroad substation in Ferrum.[5] The system utilizes thyristor-controlled reactors to produce a continuously variable inductance, and breaker-switched capacitor banks to produce discretely variable capacitance. The details of how this system achieves a balanced load is described in an ASEA brochure which is copied here as Appendix C.

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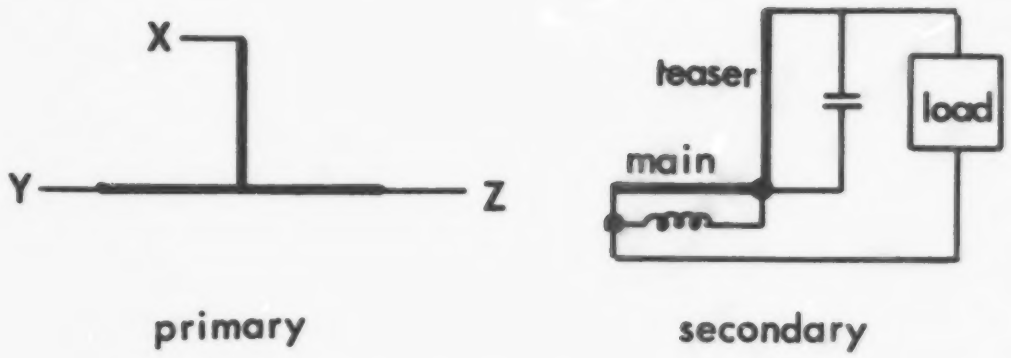

Figure B.6 Scalene Scott-connection

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Both the end feed and the Scott connection are seen to be dependent on the relative magnitude of the two loads, but the Scott connection is much more effective.

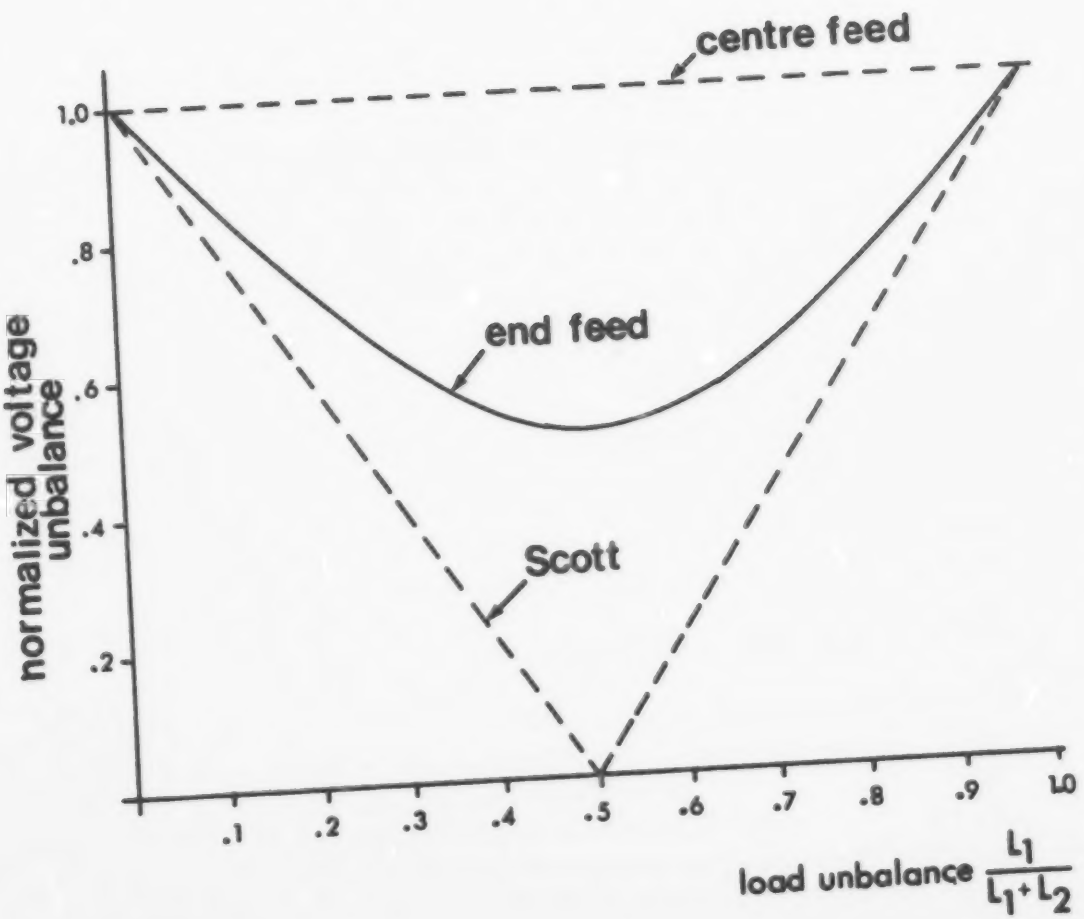


Figure B.7 Comparison of effectiveness in balancing the supply voltage

ASEA

THYRISTOR-CONTROLLED POWER FACTOR CORRECTION AND LOAD BALANCING EQUIPMENT

1.
Single phase load

In figure 1 a single phase load is connected to a three-phase grid.

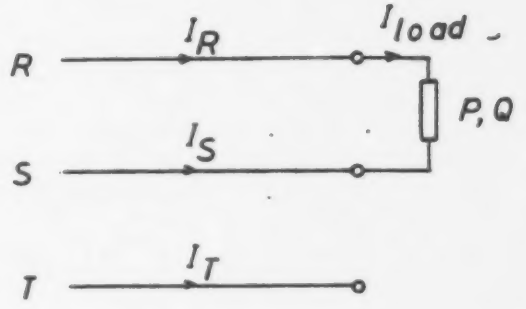


Figure 1: A single phase load connected to a three-phase power supply.

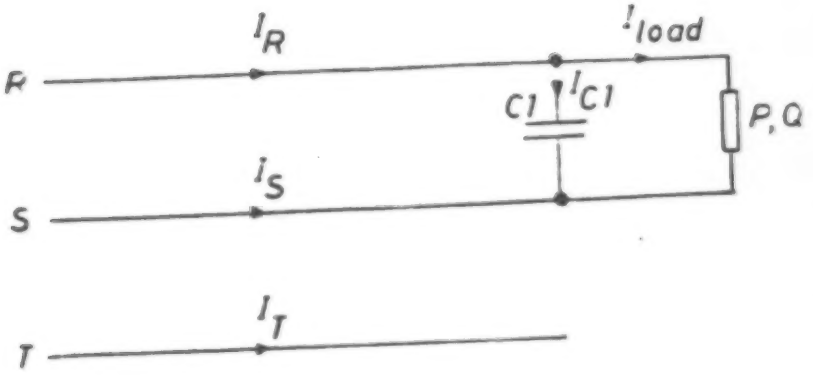
Without any compensation the line currents are given by

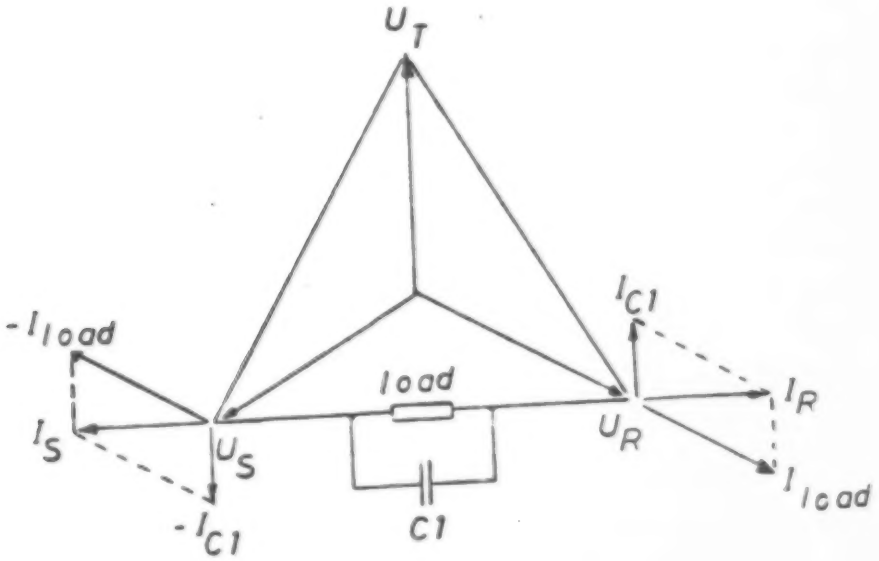
$$\bar{I}_R = \bar{I}_{load}$$

$$\bar{I}_S = -\bar{I}_{load}$$

$$\bar{I}_T = 0$$

Now capacitors C_1 connected between the same lines as the single phase load are used for displacement factor correction, i.e. for generating the reactive power consumed by the single phase load. (See figure 2.)





$$\begin{cases} I_R = I_{load} + I_{C1} = I_{RS} \\ I_S = -I_{load} - I_{C1} = -I_{RS} \\ I_T = 0 \end{cases}$$

Figure 2: Displacement factor correction.

Suppose that the reactive power generated by the capacitors is equal to the reactive power consumed by the single phase load. Then the resultant current $\bar{I}_{RS}$ must be pure active and in phase with the line to line voltage $\bar{U}_{RS}$. The line currents from the three-phase network are with $\bar{U}_{RS}$ as a reference given by

$$\bar{I}_R = \bar{I}_{load} + \bar{I}_{C1} = |I_{RS}|$$

$$\bar{I}_S = -\bar{I}_{load} - \bar{I}_{C1} = -|I_{RS}|$$

This is an unbalanced current system. Capacitors C_2 between line S and line T and line R are now used for balancing the system. (See figure 3.)

As the current in a capacitor or a reactor is leading respectively lagging the applied voltage by 90 degrees the balancing currents I_{C2} and I_L are given by

$$\bar{I}_{C2} = \bar{U}_{ST} \cdot j\,\omega\,C_2$$

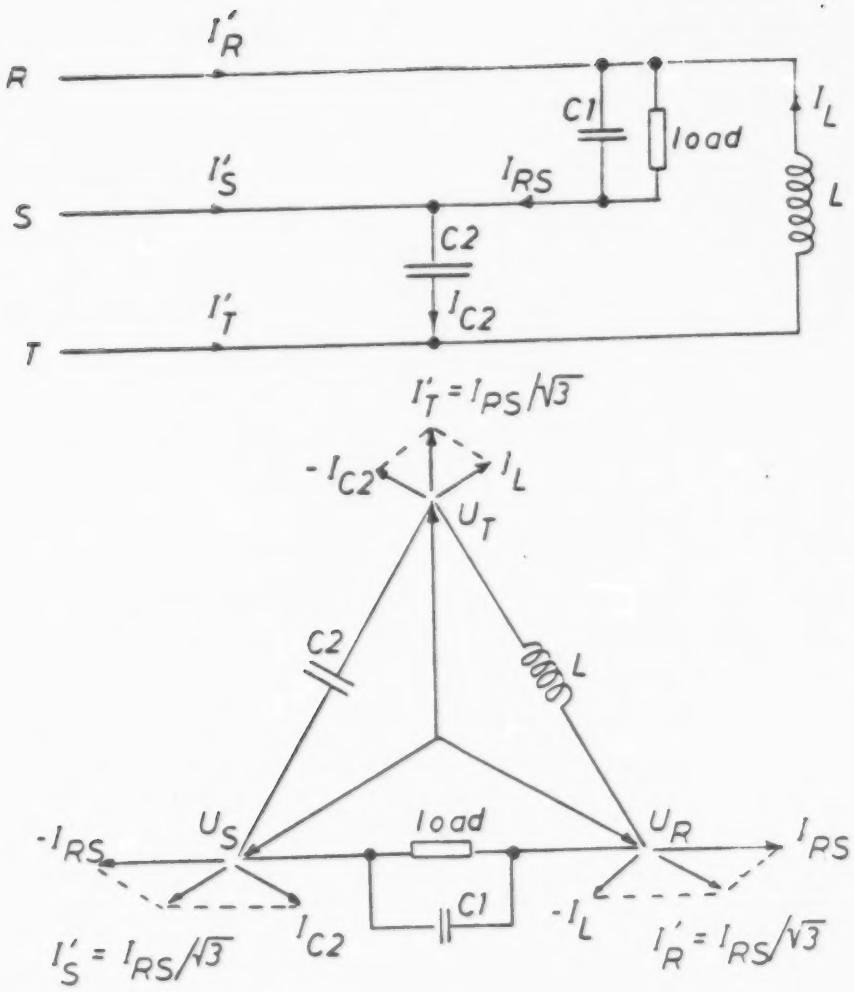
$$\bar{I}_L = \bar{U}_{TR}/j\,\omega\,L$$

Suppose that the values of C_2 and L are chosen so that the amplitude of $\bar{I}_{C2}$ and the amplitude of $\bar{I}_L$ is equal to $I_{RS}/\sqrt{3}$. The current $\bar{I}_{C2}$ is lagging the line to line voltage $\bar{U}_{RS}$ by 30 degrees because $\bar{U}_{ST}$ is lagging $\bar{U}_{RS}$ by 120 degrees. The current $\bar{I}_L$ is leading $\bar{U}_{RS}$ by 30 degrees, because $\bar{U}_{TR}$ is leading $\bar{U}_{RS}$ by 120 degrees. Hence, the balancing currents are given by

$$\bar{I}_{C2} = |I_{RS}| \cdot \frac{(\sqrt{3} - j)}{2\sqrt{3}}$$

$$\bar{I}_L = |I_{RS}| \cdot \frac{(\sqrt{3} + j)}{2\sqrt{3}}$$

The resultant currents from the three-phase system can now be calculated:



$$\begin{cases} I'_R = I_{RS} - I_L \\ I'_S = I_{C2} - I_{RS} \\ I'_T = I_L - I_{C2} \end{cases}$$

Figure 3: Balancing of the active load.

$$\bar{I}'_R = \bar{I}_{RS} - \bar{I}_L = |I_{RS}| \frac{2\cdot\sqrt{3} - \sqrt{3} - j}{2\sqrt{3}} = \frac{|I_{RS}|}{\sqrt{3}}\left(\frac{\sqrt{3}}{2} - \frac{j}{2}\right)$$

$$\bar{I}'_S = -\bar{I}_{RS} + \bar{I}_{C2} = |I_{RS}| \frac{-2\cdot\sqrt{3} + \sqrt{3} - j}{2\sqrt{3}} = \frac{|I_{RS}|}{\sqrt{3}}\left(-\frac{\sqrt{3}}{2} - \frac{j}{2}\right)$$

$$\bar{I}'_T = \bar{I}_L - \bar{I}_{C2} = |I_{RS}| \frac{\sqrt{3} + j - \sqrt{3} + j}{2\sqrt{3}} = \frac{|I_{RS}|}{\sqrt{3}} \cdot j$$

or

$$\bar{I}_R = \frac{|I_{RS}|}{\sqrt{3}} \angle -30^\circ$$

$$\bar{I}'_S = \frac{|I_{RS}|}{\sqrt{3}} \angle -150^\circ$$

$$\bar{I}'_T = \frac{|I_{RS}|}{\sqrt{3}} \angle +90^\circ$$

This means that by an accurate compensation ($Q_{C1} = Q_{load}$) of the reactive power consumed by the single phase load and an accurate balancing ($Q_{C2} = P/\sqrt{3}$ and $Q_L = -P/\sqrt{3}$) it is possible to obtain a resultant load to the three-phase network which is pure active and balanced.

The negative sign for Q_L denotes that this reactive power must be inductive.

The reactive powers needed in C1, C2 and L are given by

$Q_{C1} = Q$

$Q_{C2} = P/\sqrt{3}$

$Q_L = -P/\sqrt{3}$

so when the values of Q and P changes, the values of C1, C2 and L must also be changed. This can be arranged by using thyristor-controlled capacitors and reactors. The thyristors operate as switching elements connecting with respect to the single phase load a suitable number of stages between the three-phase lines.

The number of stages, which must be switched in, are simply determined by measuring the active and reactive powers to the single phase load. With a value of 2 MVAr per stage it is possible to obtain a compensation within $\pm$ 1 MVAr of the correct value.

2.
Two-phase load

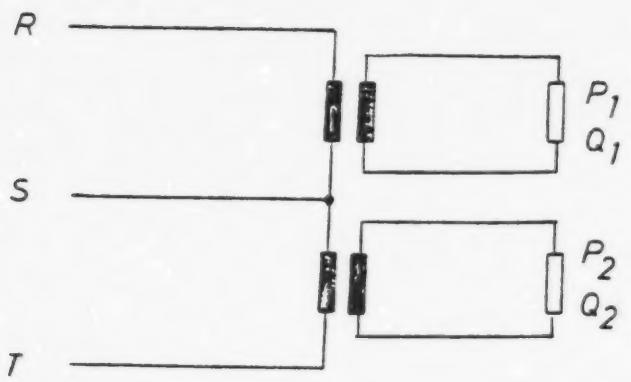
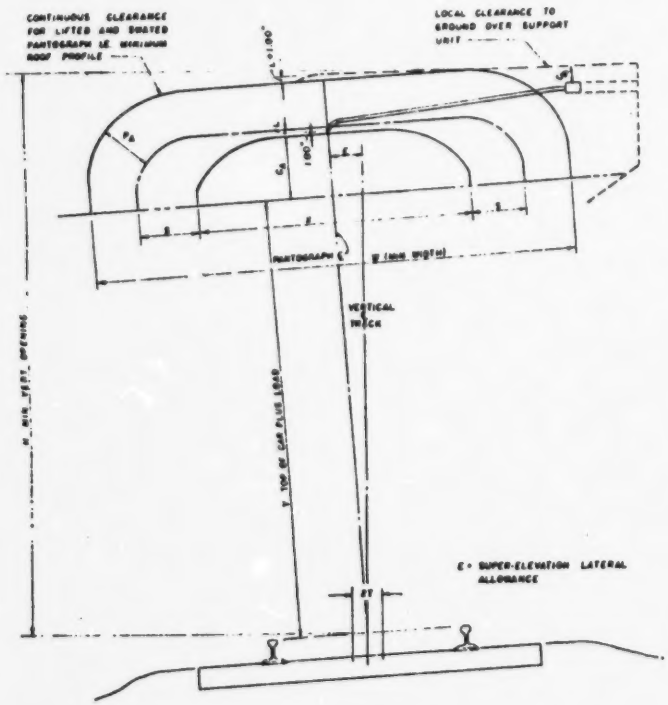


Figure 4: Two-phase load connected to a three-phase grid.

This case may be regarded as two single phase loads. The resultant reactive powers for power factor correction and load balancing are therefore given by

Resultant reactive compensation powers		Reactive powers for power factor correction and load balancing at the load	
		P_1, Q_1	P_2, Q_2
Q_{RS}	=	Q_1	$-P_2/\sqrt{3}$
Q_{ST}	=	$P_1/\sqrt{3}$	$+Q_2$
Q_{TR}	=	$-P_1/\sqrt{3}$	$+P_2/\sqrt{3}$

where the minus sign denotes an inductive reactive power.



VERTICAL STRUCTURE OPENING = H

H = $Y + C_0 + P_0 + L + E^*$

Y = MAXIMUM HEIGHT OF CAR PLUS LOAD

A = ALTITUDE COMPENSATION - CHART 4

C_0 = ELECTRICAL PASSING TO CAR CLEARANCE FROM CHARTS 2 & 4 + (C x A)

L = UPLIFT OF WIRE - STANDARD ALLOWANCE = 2" MAY BE CHANGED SUBJECT TO NUMBER OF SUPPORTS, STIFFNESS OF WIRE, ETC.)

P_0 = ELECTRICAL PASSING CLEARANCE TO FIXED MEMBER FROM CHARTS 2 & 4 + (P x A) IN LOCATION WHERE FREQUENT TRAIN STOPS ARE TO BE EXPECTED, C_0 CLEARANCES SHOULD BE SUBSTITUTED FOR P_0 IN ALL FORMULAE.

NOTE: THE 2" SHOWN AS LAST TERM IN CALCULATION OF "H" REPRESENTS 1" TOLERANCE FOR WIRE IRREGULARITIES ADDED TO BOTH C_0 & P_0

LATERAL STRUCTURE OPENING = W

W = 2S + P_0 + 2 + E + 2T

S = ALLOWANCE FOR SWAY FROM CHART 1 OR 1A

A = ALTITUDE COMPENSATION FROM CHART 4

P_0 = ELECTRICAL CLEARANCE FROM CHARTS 2 & 4 + (P x A)

W = PANTOGRAPH WIDTH (LIVE PARTS)

E = LATERAL ALLOWANCE FOR SUPER-ELEVATION WHERE APPLICABLE FROM CHART 3

T = LATERAL SHIFT OF TRACK WITHIN CIVIL ENGINEER'S TOLERANCE

NOTES:

1. THE ASSUMPTION IS MADE THAT THE CONTACT POINT OF THE PANTOGRAPH IS CENTERED OVER THE PIVOT POINT OF THE LOCOMOTIVE. WHERE THIS IS NOT TRUE ADDITIONAL CLEARANCE MUST BE DETERMINED FROM THE EXACT GEOMETRY OF THE PANTOGRAPH.
2. VOLTAGES GIVEN ARE NOMINAL SYSTEM OPERATING VOLTAGES AND CONTAIN AN ALLOWANCE FOR ± 10% VARIATION. IT IS ASSUMED THAT SUITABLE LIGHTNING PROTECTION APPARATUS IS INSTALLED.
3. PASSING CLEARANCE REFERS TO AN AIR CLEARANCE BETWEEN LIVE PARTS OF EITHER THE VEHICLE OR CATENARY AND GROUNDED PARTS OF THE FIXED STRUCTURE. IT EXISTS ONLY DURING THE PASSAGE OF THE LOCOMOTIVE OR CAR.
4. STATIC CLEARANCE REFERS TO AN AIR CLEARANCE BETWEEN LIVE PARTS OF A CATENARY STRUCTURE AND GROUNDED PARTS OF A FIXED STRUCTURE. STATIC CLEARANCES (NOT PASSING CLEARANCES) APPLY TO CATENARY TO MAXIMUM CAR (INCLUDING ITS LOAD)
5. WHERE CONTACT WIRE IS OFF-CENTER ACCOUNT MUST BE TAKEN OF ADDITIONAL TILTING OF THE PANTOGRAPH AND CLEARANCES ADJUSTED ACCORDINGLY.
6. NO RECOMMENDATIONS ARE MADE AS TO STANDARD OR NORMAL CONTACT WIRE HEIGHT OR CLEARANCES. THESE WILL BE GOVERNED BY OPERATING CONDITIONS AND REQUIREMENTS. WHERE TROLLEYS ARE PERMITTED OR REQUIRED TO GO ON TOP OF ROLLING STOCK, CONTACT WIRE HEIGHT REQUIREMENTS WILL BE GREATER THAN WHERE SUCH PRACTICE IS PROHIBITED.
7. VERTICAL OPENING ASSUMES SINGLE CONTACT WIRE. IF MESSENGER WIRE IS USED OPENING MUST BE INCREASED BY THE MESSENGER TO CONTACT WIRE SPACING.

THIS DIAGRAM SHOWS RECOMMENDED MINIMUM CLEARANCES. THEY ARE BASED ON CLASS 6 TRACK AND STATIC DEFLECTION. HIGH SPEED OPERATIONS ON OTHER TRACK CLASS REQUIRES "S" TO BE INCREASED IN PROPORTION TO DYNAMIC MOVEMENT OF THE VEHICLES TO BE OPERATED. DETAILED ENGINEERING INVESTIGATIONS MAY RESULT IN DEVIATIONS.

(S) BASIS FOR LATERAL DISPLACEMENTS

CHART 1 VALUES FOR LOCOMOTIVES

CLASS 6 TRACK CONDITIONS ABOVE ITEM 2 FOR LOWER CLASS	DISPLACEMENTS IN INCHES (ONE SIDE ONLY)			
PANTOGRAPH HEIGHT ABOVE RAIL	14'-00"	16'-00"	22'-00"	25'-00"
1 LATERAL	1.00"	1.00"	1.00"	1.00"
2 SIDE BEARING TILT	1.06"	1.57"	1.61"	2.17"
3 SPRUNG "J" DIFFERENCE IN HEIGHT	0.72"	3.02"	4.30"	5.17"
4 BOLSTER SWING (NEGLECTED)				
5 RAIL-0 DIFFERENCE IN HEIGHT AT 56½" GAGE	1.40"	1.95"	2.54"	3.35"
6 PANTOGRAPH SWAY	0	1.00"	3.00"	4.12"
TOTAL S	5.23"	10.51"	16.61"	19.01"

CHART 1A VALUES FOR M-U CARS

PANTOGRAPH HEIGHT ABOVE RAIL	14'-00"	16'-00"	22'-00"	25'-00"
1 LATERAL	2.00"	2.00"	2.00"	2.00"
2 SIDE BEARING TILT	------	------	------	------
3 CAR BODY ROLL (3°)	8.80"	11.95"	13.86"	15.72"
4 BOLSTER SWING	------	------	------	------
5 RAIL-0 DIFFERENCE IN HEIGHT AT 56½" GAGE	1.40"	1.95"	2.54"	3.35"
6 PANTOGRAPH SWAY	0	1.00"	3.00"	4.12"
TOTAL S	12.20"	17.90"	21.40"	25.19"

(P) (C) AIR CLEARANCES

CHART 2 CLEARANCES AT TUNNELS & BRIDGES TO GROUNDED STRUCTURES

NOMINAL SYSTEM VOLTAGE	NORMAL P	NORMAL C	RECOMMENDED ABSOLUTE MINIMUM P	RECOMMENDED ABSOLUTE MINIMUM C
1.5 KV (D.C.)	4	3	3	3
3.0 KV (D.C.)	4	4	3	3
12.5 KV (A.C.)	6	7	3	5
25.0 KV (A.C.)	8	9½	6	8
50.0 KV (A.C.)	10	21	10	10

P = ELECTRICAL PASSING CLEARANCE INCHES
C = STATIC ELECTRICAL CLEARANCE INCHES

(E) SUPER-ELEVATION ALLOWANCE

CHART 3 ALLOWANCE AT PANTOGRAPH - WIRE CONTACT

E = INCHES LATERAL

SUPER-ELEVATION INCHES	DISPLACEMENT AT HEIGHT ABOVE RAIL 14'0"	19'0"	22'0"	25'0"
1	0.973	1.033	1.072	1.109
2	1.94	2.07	2.14	2.22
3	2.91	3.11	3.21	3.33
4	3.88	4.14	4.28	4.44
5	4.86	5.18	5.36	5.55
6	5.83	6.21	6.43	6.66

NOTE: APPLIES IF CENTERLINE OF TRACK IS LOCATED AT CENTER OF TUNNEL OR BRIDGE. ALLOWANCE FOR SUPER ELEVATION MAY BE DECREASED IF TRACK IS MOVED OFF-CENTER TO COMPENSATE.

(A) ALTITUDE COMPENSATION

CHART 4

ALTITUDE	A MULTIPLY BY
0 - 3000 FT.	1.00
3000 - 4000 FT.	1.02
4000 - 5000 FT.	1.05
5000 - 6000 FT.	1.08
6000 - 7000 FT.	1.12
7000 - 8000 FT.	1.16
8000 - 9000 FT.	1.20
9000 - 10000 FT.	1.25

PROPOSED CLEARANCE SPECIFICATIONS TO PROVIDE FOR ELECTRIFICATION

NO SCALE | SEPTEMBER 11, 1975

APPENDIX D

A.R.E.A. CLEARANCE RECOMMENDATIONS

APPENDIX E

CATENARY DESIGN

E.1 DESIGN FOR DYNAMICS

The dynamics of the catenary depends on its vertical elasticity, the frequency response of the catenary, and the built-in sag of the contact wire.

The vertical elasticity basically depends on the span, the support at the masts, and the wire tension. To reduce the variation in the elasticity over the span, it is desirable to elastically support the contact wire near the masts. Thus, a stitch-wire configuration is often adopted (see Figure 3). Equation 1[1] provides a relatively simple model for calculating the vertical elasticity for a 'stitched-sagged catenary'.

$$n_x = \frac{100\ X\ (L-X)}{L\ (T_m+T_c)} \quad \text{cm/Newton} \qquad (1)$$

$$\text{for } L \leq X \leq A$$

where: A = distance from support to stitch wire attachment section

L = span, in metres

T_m = tension in messenger wire, Newtons

T_c = tension in contact wire, Newtons

At the centre of the span, $n_c = \frac{25\ L}{(T_m+T_c)}$

Note that increasing the wire tension decreases the elasticity. Also, decreasing the span decreases the elasticity (the motion of the contact wire as the pantograph passes decrease).

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1 From FRA-ONECD-75-5, North East Corridor High-Speed Rail Passenger --- converted to SI units.

The critical frequency of the catenary may be approximated by equation 2 .

$$f_c = \frac{K}{L}\sqrt{\frac{T_m + T_c}{Q_m + Q_o + Q_c}} \quad \text{Hertz} \qquad (2)$$

where: T_m = tension in the messenger wire, Newtons

T_c = tension in the contact wire, Newtons

Q_m = mass of the messenger wire per unit of catenary length, kg/m

Q_o = mass of the dropper wires per unit of catenary length, kg/m

Q_c = mass of the contact wire per unit of catenary length, kg/m

L = span, m

K = an experimental constant, lying between 0.435 and 0.480.

The higher the critical frequency, the faster a train may travel for a given pantograph spacing. Thus, increasing the wire tension and reducing the catenary mass is desirable. Decreasing the span length also increases the critical frequency.

The critical speed for a multiple pantograph train is approximated by equation 3.

$$V_c = \frac{3600}{1000} f_c \cdot D \quad \text{km/h} \qquad (3)$$

where D equals the minimum pantograph separation, in metres.

E.2 WIND AND ICE LOADS

The designer of the catenary for the North East Corridor in the United States used the following criteria for wind and ice loads:

DESIGN WIND VELOCITY = 55 MPH (88.5 KM/H)

ICE LOAD = 1 IN (2.54 CM) RADIAL THICKNESS

Investigation of power utility design practice reveals that each has their own design criteria, although the variation is not great. Ontario Hydro uses[2] the following criteria for wind and ice loads:

DESIGN WIND PRESSURE = 0.383 kPa (EQUIVALENT TO 60 MPH)

ICE LOAD = 12.7 MM RADIAL THICKNESS

The loads are assumed to occur simultaneously.

Recent extensive testing by Ontario Hydro[3] reveals that the design criteria are very conservative. Test results indicate that an ice build-up of 17 mm radial thickness occurred with a 6 m/s wind (21.6 km/h or 13.4 mph), and an ice build-up of 3.5 mm radial thickness occurred with a 13 m/s wind (46.3 km/h or 29.1 mph). A design practice of 6.4 mm of ice with the 0.383 kPa wind pressure is indicated.

Based on an evaluation of mast design using the various criteria, and considering experimental results, we recommend that the Ontario Hydro design criteria of 6.4 mm of radial ice with a 0.383 kPa wind pressure be adopted. The column design should be checked for a radial ice load of 25.4 mm, with no wind, for buckling.

E.3 CURVE TENSION

The high wire tension required to improve the dynamic response of the catenary imposes additional loading on the tension masts and on catenary masts adjacent to curved track. Modern catenary design for high-speed operation requires that the contact and messenger wire tensions be maintained constant by constant tension devices, typically a pulley and weight system.

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2 "Wind and Ice Loads on Overhead Transmission Lines," S. Kresknasamy, Ontario Hydro Research Review, No. 3, June 1981.

3 Ibid

Wire tensions being considered for the 4/0 and 1/0 catenary configuration, using cadmium-copper wire, are 28.95 and 14.44 kN respectively. To achieve the contact wire tension, a 2-to-1 pulley system and a 1,476 kg mass is required. The messenger wire requires a similar arrangement with a 736 kg mass. The contact wire wears during service, and therefore becomes lighter in weight. To maintain the proper wire/rail clearance, and the appropriate contact wire sag, it will be necessary to reduce the contact wire tension over its service life (of approximately 30 years, depending on traffic). Thus, the contact wire tensioning weight would be reduced to 1,033 kg mass near the end of the wire life.

The wire tension imposes a moment on the masts at curves. The moment increases as the degree of curvature increases. Masts on curves exceeding one degree may require guys to offset the moment. In addition, the limits on wire stagger (off the track centre-line) require that mast spacing be decreased as shown in Table E.1.

TABLE E.1

MAST SPACING ON CURVES

Degree of Curvature	Radius of Curve, m	Maximum Mast Spacing, m
1°	1,746	73.0
2°	873	51.6
3°	582	42.1
4°	437	36.5
5°	350	32.6
6°	292	29.8

* for a 'stagger' of +10 inches, -5 inches on curves

Report on Assignment 4

Catenary/Pantograph Systems

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Your committee submits for adoption and publication in Chapter 33 of the Manual the following new Part 4.

Part 4

Catenary/Pantograph Systems

4.1 CONTACT WIRE AMPACITY

4.1.1 INTRODUCTION

The contact wire of a catenary system must perform its function of transferring power from the fixed distribution system to the moving vehicle under some harsh physical and electrical conditions without exceeding any limitations which would reduce its life or effectiveness as a critical part of a railway electrification installation. In most catenary system designs the contact wire must be maintained at a relatively high tension in order to insure smooth tracking of the vehicle-mounted pantograph for the collection of power. The copper or copper alloys generally used for contact wires suffer irreversible reduction in their strength when heated above their annealing point and are thus subject to breaking below their designed tensions.

Temperature rises in a contact wire are usually produced through the cyclic interactions of many different parameters and must be thoroughly investigated for each circumstance. This document gives the preferred method for calculating contact wire ampacity as well as a table of calculated continuous contact wire currents for various wire sizes and alloys under a set of typical assumed conditions.

4.1.2 METHOD OF CALCULATING AMPACITY

The recommended technique for calculating the ampacity of contact wires was developed by Messrs. H. E. House and P. D. Tuttle and published in the AIEE Transactions Paper No. 58-41 dated February 1958. This technique essentially balances the heat gained and lost by the wire through current heating, solar heating, convection and radiation. The referenced AIEE paper contains tables and charts of different variables which are subject to temperature, altitude, and solar angle and should be consulted for any detailed engineering investigations. The basic equation follows.

$I^2r = q_c + q_r - q_s$ when q_c = convected heat loss

q_r = radiated heat loss

q_s = heat gained from solar and sky radiation

The right hand terms are then expanded to yield the following detailed equation:

$$I = \sqrt{\frac{\left[1.01 + 0.371\left(\frac{D\rho_f V}{\mu_f}\right)^{0.52}\right] k_f (t_c - t_a) + 0.138\, D\alpha}{\left[\left(\frac{K_c}{100}\right)^4 - \left(\frac{K_a}{100}\right)^4\right] - \frac{\alpha(Q_s \sin\theta + Q_d)\, A'}{r}}}$$

Where

D = Conductor diameter in inches

ρ_f = Density, pounds of air per cubic foot

V = Velocity of air in feet per hour

μ_f = Absolute viscosity of air in pounds per hour per foot

k_f = Thermal conductivity of air in watts per square foot per degree Celsius

t_c = Conductor temperature in degrees Celsius

t_a = Ambient temperature in degrees Celsius

$T_f = \frac{T_c + T_a}{2}$ air film temperature in degrees Celsius

ϵ = Thermal emissivity constant for the conductor surface

K_c = Conductor temperature in degrees Kelvin

K_a = Ambient air temperature in degrees Kelvin

α = Solar absorption coefficient

Q_s = Direct solar radiation in watts per square foot

Q_d = Sky radiation in watts per square foot

A' = Projected area of the wire in square feet per lineal foot $= \frac{D}{12}$

$\theta = \cos^{-1}|\cos H_c \cos(Z_c - Z_s)|$ where

H_c = altitude of the sun above the horizon, degrees

Z_c = azimuth of the sun, degrees

Z_s = azimuth of the wire, degrees

r = Effective a-c resistance in ohms per foot

I = Continuous current in amperes

4.1.3 UNIFORM RATING PARAMETERS

Any meaningful ampacity comparison between wires of different sizes and different compositions must be based upon a uniform set of conditions. The conditions outlined below represent typical conditions encountered through much of North America and permit a realistic comparison of wire sizes and compositions as they affect the continuous ampacity rating. These are referred to as standard conditions.

Ambient air	25°C
Conductor operating temperature, hard-drawn copper	75°C
Conductor operating temperature, alloys	100°C
Emissivity	0.5
Frequency of power system	60 Hz
Wind velocity	2 ft/sec

Resistance, ohms per circular Mil/foot at 20°C

Hard-drawn copper	10.674 ohms
ASTM alloy 80	12.964 ohms
ASTM alloy 55	18.857 ohms
Worn wire	70% of original section

Other factors taken from tables in AIEE paper 58-41.

4.1.4 SAMPLE CALCULATION

The following example of a typical calculation is shown for illustrative purposes. The wire used in the calculations is a 4/0 grooved hard-drawn copper contact wire worn to the 70 percent point.

$$I = \sqrt{\frac{\left[1.01 + 0.371\left(\frac{0.442 \times 0.068 \times 7200}{0.0473}\right)^{0.5}\right]}{0.00852\,(75 - 25) + 0.138 \times 0.442 \times 0.5\left[\left(\frac{348}{100}\right)^{0.5} - \left(\frac{298}{100}\right)^{0.5}\right] - \frac{0.5\,(95.3)\,0.036}{0.0000872}}}$$

$$I = \sqrt{\frac{13.11 + 2.06 - 1.72}{0.0000872}}$$

I = 393 amperes

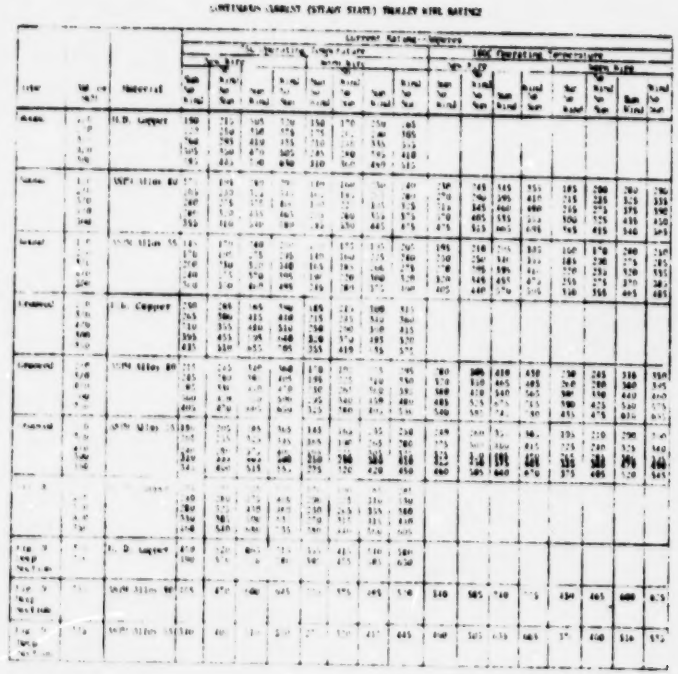
Note: The 3-amp difference between the sample calculation result and the computer derived results in the following table is due to rounding of numbers and using tabulated values of q, found in the House and Tuttle paper.

4.1.5 TABLE OF CONTINUOUS AMPACITY RATINGS

The following table of continuous (steady state) current ratings of various sizes of trolley (contact) wire are given for comparative purposes and should be used with appropriate engineering discretion. Detailed designs of a catenary system should take into full account the short-time ampacity ratings (one to three minutes) and the loading cycles expected to be generated by the operation of trains. Overall electrification system designs may cause some sections of catenary to endure abnormal loading cycles and consequently require increased wire size or the use of a parallel feeder. Care should be taken to determine the current sharing between the wires making up the catenary system caused by mutual impedance and possible composition differences of the wires. Operating temperatures of the alloys used in the tables are as follows:

Hard-drawn copper	75°C
ASTM alloy 80	100°C
ASTM alloy 55	100°C

A precautionary prediction of loss in wire tensile strength due to annealing at elevated temperatures should be made for the design by a proper evaluation of the expected wire temperature-time experience under system overload conditions since the effects are *cumulative* and *permanent*.



GLOSSARY

APPENDIX G

Auxiliary Contact Strip: A light, particularly flexibly-sprung contact which should remain longer in contact with the contact wire than the main contact strip(s).

Booster Transformer: An electrical transformer with its primary winding in series with the catenary feed wires and its secondary winding connected to an insulated return wire. Use of this device reduces the ground return currents, thereby reducing the induction effect in parallel conductors.

Contact Strip Assembly: Assembly comprising the wearing strip and its mounting.

Contact Strip Support or Pan: Pan frame supporting or joining the contact strips. In German, the term 'schleifstückträger' is used for arrangements with one contact strip, and 'palette' for arrangements with more than one strip.

Contact Strip: Replaceable part of the pantograph pan used for current collection.

Electromagnetic Compatibility: The situation where one electromagnetic system may be operated without producing an unacceptable influence on neighbouring electromagnetic systems.

Horn: Curved ends of the pantograph head which ensure movement onto the contact strip of out-of-running wires.

Pantograph: Apparatus for collecting current from one or more contact wires, formed of a hinged device designed to allow a vertical movement of the contact strip. The design differs depending on whether the pantograph is for alternating current, direct current or multiple systems.

Pantograph Head: The part of the pantograph carried by the apex joint comprising guides, springs, pan frame or pan tube and contact strips (replacing IEC 30-15-890).

Voltage Imbalance: A measure of the deviation, in both magnitude and phase angle, of individual phase voltages in a three-phase supply from a balanced situation where the magnitudes are equal with a 120°, 240° and 360° phase relationship.

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